Summer 1988

Principles of Design for Complex Displays: A Comparative Evaluation

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A Comparative Evaluation

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M.S. August 1986, Old Dominion University

A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Psychology

Old Dominion University
July, 1988

Approved by:

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ABSTRACT

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The present study examined the main and interactive effects of information format, information density, principle of information grouping, orientation of the airspeed scale, and task type on response time (RT) and accuracy in a decision making task. Forty-eight college students viewed static displays of primary flight instruments and signaled responses to the displays by pressing keys on the computer keyboard. Three levels of task type were employed. In the current state estimation task, subjects were required to determine whether each individual instrument reading was within prespecified limits. In the future state estimation task, subjects were required to attend to the relationship between instrument readings, and to estimate the implication of these relationships for future flight conditions. In the combined task condition, subjects completed both the current and the future state estimation tasks during each experimental trial. All subjects were exposed to three levels of information format (analogue, digital, or combined analogue and digital displays), and to three levels of information density (low, medium, or high).

Results of the study indicate that an interaction of information format and task type significantly affected RT and percent correct response. Performance in current task conditions was enhanced when subjects viewed digital displays, while analogue displays benefited performance in future task conditions. RT was longest, and accuracy was lowest, when subjects were in the future task by digital information format conditions. Reversing the airspeed scale degraded performance across task types, and across all levels of information format. However, the reversed airspeed scale degraded performance most severely in conditions of future state estimation and digital informat format. The grouping principle variable moderated performance only for tasks in which the relationship between stimulus readings determined the correct or incorrect identity of the instrument readings (future state estimation). For future task conditions, sequential grouping provided shorter RT, but lower percent correct response, than did functional grouping. No effect of information density was obtained. This finding probably was due to the manner in which information density was operationalized in the current study. The study findings are discussed in terms of their implications for the design of complex displays.

Acknowledgments

I would like to express my deep gratitude to Dr. Glynn Coates who served as the Director of my Dissertation Committee. Dr. Coates shared his extensive knowledge, valuable time, and good sense of humor with me during the process of completing this project. Over the course of my graduate study, Dr. Coates consistently has been willing to help, but never has been willing to share the credit when the work was completed. I have profited greatly from my association with Dr. Coates, and I am proud to have been one of his students.

I also would like to thank the remaining members of my committee. Dr. Ray Kirby has helped in too many ways to list. However, he must remember how many times he calmed my troubled soul. To Dr. Kirby goes my special thanks. Dr. Randy Harris provided a blend of exceptional expertise and good common sense that provided one of the most profitable and enjoyable learning experiences of my career. I also would like to thank Dr. Fred Freeman. Although Dr. Freeman contributed to this project in many ways, I am especially grateful to Dr. Freeman for his insightful comments and suggestions.

Joan Moore contributed her knowledge of computer programming and created the software that enabled me to collect my data. I also would like to express my gratitude to Ms. Moore for her willingness to share new computer programming techniques with me, and for her excellent observation skills and consistent good humor.

The assistance of my family, Loren, Justin, and Chris Converse, was constant, even in times when my response to the demands of this project was reflected in chronic bad temper. These individuals know how much I love and appreciate them, but they deserve my extra special thanks.

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Principles of Design for Complex Avionic Displays: A Comparative Evaluation

Cockpit displays transmit information that is generated by avionic sensors to members of the air crew. In early flight systems, information was presented to pilots on a relatively small number of electro-mechanical instruments, each of which reflected the status of one flight parameter (Hollister, 1983; Hunt, 1983; Wherry, 1984). The function of the pilot was to monitor the instrument panel, to integrate mentally the displayed information, and to provide inputs to the system via flight controls (Chorley, 1984; Klein & Cassidy, 1972).

Early efforts to improve cockpit displays were based on the study of visual perception. During and shortly after World War II, attempts to improve visual displays focused on accommodating the sensory properties of the human eye. The measure of an effective display was the degree to which it facilitated the rapid detection of a stimulus signal (Paden, 1981; Grossman, 1983; Hollister, 1983; Roscoe, 1968). Many of the design principles that were developed during this period continue to be used today. For example, guidelines for evaluating the luminance of a display and its surround, the acceptability of the visual angle at which a display must be viewed, and the effectiveness of chromatic and achromatic contrast continue to be used in the evaluation of contemporary displays (Booth & Farrell, 1979; Hollister, 1983; Lyons & Roe, 1980; Snyder & Bogle, 1984).

As technological advances made possible the creation of new flight systems and subsystems, additional instruments were added to the cockpit. Initially, growth in the amount of information available to pilots was considered to be a positive factor. Cockpit designers assumed that large data bases would improve decision making by giving pilots a more complete overview of total system functioning (Boucek, Pfaff, & Smith, 1983; Paden, 1981). Thus, the beneficial effects of displaying increasingly large amounts of data were not weighed against the potential danger of overloading pilots with too much information (Adams, 1982; Companion & Sexton, 1982; Dorris, Sadosky, & Connolly, 1977).

By the mid-1960s, the mass of information that could be detected by avionic sensors was too large to be displayed within the limited confines of the cockpit (Chorley, 1981; Schmidt, 1984). In addition, evidence that pilots were being supplied with more information than they could use effectively began to appear in the literature. Researchers reported that display clutter was the most common complaint registered by pilots in evaluations of cockpit instrument panels (Kirkland et al., 1962; Roscoe, 1968). Such data underscored the fact that the amount of information provided to air crew members could not continue to expand indefinitely (Eggleston, Chechile, Fleishman, & Sasseville

1986; Dorris, Sadosky, & Connolly, 1977; Schultz, Nichols, & Curran, 1985).

Serial Information Processing and Limited Capacity

The human information processing system is limited in its capacity to encode information from the environment (Broadbent, 1958; Hick, 1952; Moray, 1980). Although there currently is disagreement about the exact process by which the human brain encodes information, most researchers agree that, at least in some situations, stimuli are encoded in a sequential or serial fashion (Howell, 1982; Lane, 1982; Sternberg, 1966; 1969). The encoding of a stimulus is not an instantaneous event. Rather, the encoding of each stimulus consumes a specific amount of time. Thus, when stimuli are encoded in a serial fashion, a large stimulus set will take longer to encode and process than will a small stimulus set (Hick, 1952; Neisser, 1967; Smith, 1968).

Support for serial information processing is derived from numerous studies in which a strong linear relationship between response time (RT) and the number of stimuli in a stimulus set has been found (Alluisi, 1970; Hick, 1952; Kahneman, 1973; Kantowitz, 1981; Sternberg, 1969). Several researchers report that over 80% of the variance in subject response time is explained by the size of the stimulus set (Bishu & Drury, 1986; Conrad, 1955; Dorris et al., 1977).

In relation to the avionics environment, the Theory of Serial Information Processing predicts that increasing the amount of information to which pilots must attend will increase mental workload and delay responses to changes in system state. When flight sensors transmit more information than the pilot can encode and process, specific pieces of information must compete for the pilot's attention (Howell, 1982; Kahneman, 1973). The greater the amount of information transmitted, the greater is the competition among specific pieces of information for the attention of the system operator (Banks, Gilmore, Blackman, & Gertman, 1982; Broadbent, 1958; Koonce & Moroze, 1982). As a result of this competition, the likelihood of information processing errors increases and air crew performance is likely to be degraded (Schmidt, 1984; Williams, 1982). Thus, the design of effective visual displays for modern aircraft requires a systematic effort to reduce the attention and information processing demands of the modern cockpit environment (Adam, 1981; Carel, 1965; Chorley, 1984).

Strategies to Reduce Cockpit Workload

Display of Relevant and Essential Information

In order to reduce mental workload in the cockpit, display designers are advised to present only "relevant and essential information" to the air crew (Schultz, Nichols, &

Curran, 1985; Murphy & Mitchell, 1986). Unfortunately, this recommendation provides little assistance to designers of avionic displays because there is no clear agreement about what constitutes "relevant and essential information" in the cockpit (Banks et al., 1983; Huntoon, 1983). While some definitions of what constitutes important cockpit information have been proposed, there is no general agreement as to the validity of these definitions. In addition, the vague terms that are employed in such definitions are likely to be understood differently by various designers of complex displays (Companion & Sexton, 1982; Hollister, 1983). In summary, an exact description of what information should and what information should not be displayed on the aircraft instrument panel has not been determined. As a result, there currently is no objective method of measuring display clutter (Eggleston, Chechile, Fleishman, & Sasseville, 1986; Wherry, 1984).

Designers generally prefer to cope with the question of what information to provide to crew members by risking the presentation of too much information, rather than by risking the deletion of important data (Koonce & Moroze, 1982). This trend is encouraged by regulations of the Federal Aviation Agency that require specific pieces of information to be available to pilots at all times. In addition, aircraft manufacturers are hesitant to alter display formats in a radical way, due to fears of adverse pilot reaction that can, in turn, reduce sales. While these concerns and policies are defended on the grounds of flight safety and sound economic policy, they have hindered efforts to alleviate clutter and confusion in the modern cockpit.

Grouping of Related Information

Due to the difficulties encountered in defining and displaying relevant and essential cockpit information, a second method of reducing pilots' mental workload recently has captured the attention of human factors researchers and designers of complex displays. This method involves the creation of visual display formats that combine data into cohesive groupings (Baty & Watkins, 1979; Goldsmith & Schvaneveldt, 1984).

The belief that the grouping of related information will reduce mental workload is derived from Miller's concept of information "chunking" (Miller, 1956). According to Miller, human observers are not limited strictly to processing information in a serial fashion. Rather, human observers reduce the demand imposed on short term memory by integrating discrete pieces of data and encoding the resulting "chunk" as one unit of information.

Sensory information must be gathered and interpreted in terms of a coherent framework if information processing is to be efficient. This framework is supplied by the beliefs an observer has about the types of information that are characteristic of a specific phenomenon. Thus, observers integrate discrete pieces of information that are related to a specific object, person, or environmental circumstance.

Observers form ideas about the relationships that exist between characteristics of an object or between characteristics of an environmental situation as a result of past experience with the environment (Rosch, 1975; Smith, Shoben, & Rips, 1974). For example, early in life, most observers decide that, if a small animal with four legs and a tail makes a barking sound, it is called a dog. However, if a similar animal makes a different sound, the observer determines that the animal is called a cat. In the same way, young observers of the world determine that certain sets of information are characteristic of a normal situation, while other sets of information provide evidence that something is amiss in the environment.

Once an observer forms a belief about the types of information that characterize an object or a situation, the belief is stored in long term memory as a prototype or schema. As individuals grow and learn, many schema are accumulated. These schema then direct the observer's attention to specific stimuli, and determine what information will be integrated (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). For example, when an observer tentatively identifies an object within the environment, the schema for that object is retrieved from long term memory. The schema then directs the observers attention to other stimuli that also are believed to characterize the object. In effect, the observer is searching for evidence that the initial identification of the object is correct. If the tentative hypothesis is confirmed, all information relating to the identified object can be "chunked" together and processed as one unit (Neisser, 1976; Stern, 1985; Taylor & Crocker, 1981).

Schema not only allow observers to process information efficiently, they also drive the observer's response to the environment (Casey, Kramer, & Wickens, 1984; Garner & Felfoldy, 1970; Hintzman & Ludlam, 1980; Stern, 1985). When an observer perceives the relationships between stimulus inputs correctly, an accurate understanding of the environment is fostered. This comprehension enhances the observer's ability to respond appropriately to external stimuli. However, when the relationship between various pieces of information is unclear, or when unrelated pieces of information are combined erroneously, an observer's concept of the environment is faulty, and responses to the environment are likely to be inappropriate or inefficient (Grossman, 1983; Koonce et al., 1982; Morrison, 1986).

Thus, in order for an observer to respond correctly to the environment, he or she must perceive the relationships between stimulus inputs correctly.

Miller's (1956) "chunking" concept is the basis of the integrated display format, a design technique that mechanically combines related information into well defined groups <u>before</u> the information is displayed. The result of the mechanical "chunking" then is displayed in graphic or pictorial form. Because information is integrated before it is displayed, pilots are relieved of the need to determine informational relationships. Thus, cognitive workload should be decreased. The mechanical "chunking" of information also advises pilots of the relationships that exist between specific pieces of information. This process should help to increase and refine the pilot's knowledge of overall system functioning (Bishu & Drury, 1986; Caraux & Wanner, 1979; Roscoe, 1968; Schmidt, 1984).

Unfortunately, the success of integrated displays has been mixed. Several authors report that the operators of complex systems demonstrated improved performance when system status information was displayed in an integrated form (Craik & Lockart, 1972; Hunt, 1983; Huntoon, 1983; Medin, Alton, Edelson, & Freko, 1982). However, these optimistic findings are counterbalanced by evidence that integrated displays do not always improve performance. In some cases, integrated displays seem to increase, rather than decrease, the cognitive complexity of monitoring and deciphering system status information. Carswell and Wickens (1984) and Baty and Watkins (1979) obtained no performance gain when integrated displays were substituted for traditional electro-mechanical aircraft instruments. Casey (1986) obtained no support for the hypothesis that RT and errors decrease as a negative function of the amount of information integrated. In addition, several researchers reported no significant difference in performance across integrated and nonintegrated displays (Benbasat & Taylor, 1982; Blomberg & Pepler, 1983; Chorley, 1984; Koonce et al., 1985).

Explanations of Information Integration Results

Grouping Principles. Several explanations of the inconsistent effects of information integration have been offered. Bishu and Drury (1986) suggested that inconsistent findings were due to the fact that the basis for integrating information was not consistent across studies. According to Bishu and Drury, more than 14 independent principles for grouping information are recommended by display designers and human factors experts.

Three principles of information grouping have received the most extensive research attention. These principles are: 1) sequential grouping; 2) grouping according to frequency of use; and 3) functional grouping. Proponents of sequential grouping suggest that information that a system operator uses at the same point in time should be grouped together. Temporal relationships between the use of specific pieces of information generally are identified in a procedural flow analyses (Meister, 1985). An excellent example of information integration that is based on the principle of sequential grouping of information is the design of multifunction cockpit displays. These displays provide different information on a CRT screen, depending on the phase of flight (Companion & Sexton, 1982; Hunt, 1983).

The frequency grouping principle recommends that data be grouped according to how often specific pieces of information are required for operator decision making. Information to which the system operator refers most frequently are placed in close proximity, and are positioned in a central location that is well within the operator's normal field of view. On the other hand, information that plays a less central role in operator decision making is placed in the periphery of the operator's field of view. The frequency with which specific types of information are used often is determined on the basis of expert opinion. However, frequency of use information can be evaluated most precisely by link analysis techniques (Meister, 1985; Pennington, 1982). An excellent example of information that is integrated according to the frequency grouping principle is the basic "T" configuration for primary flight instruments. This instrument panel design was derived from link analyses of pilots' eye movement patterns and positions instruments, in part, according to how often pilots scan each instrument (Fitts, 1951; Fitts, Jones, & Milton, 1949; Harris, & Spady, 1985; Spady & Harris, 1983; Tole, Stephens, Vivaudou, Ephrath, & Young, 1983).

The functional grouping principle suggests that data should be grouped according to the unique information needs of a specific task or activity. Thus, the prerequisite for functional grouping is the identification of discrete tasks or activities that must be performed by the operator of a complex system. Designers can obtain such task-analytic information most accurately by completing a procedural analysis of system operation (Meister, 1985). Once discrete tasks or activities have been identified, information relating to each task or activity should be grouped together on a separate area of the instrument panel (Boles & Wickens, 1983; Roske-Hofstrand & Paap, 1985). The common practice of displaying primary flight information and navigational data on separate areas of the instrument panel is an example of functional grouping.

Each of the proposed principles of information grouping has received some support in the literature. This fact has led many human factors specialists to suggest that designers should follow the recommendations of all of the principles for grouping information (Murphy & Mitchell, 1986; Summers & Erickson, 1984). However, this suggestion rarely can be implemented because the various grouping principles often provide contradictory recommendations. For example, if several pieces of information relate to the same functional activity, but each is required with different frequency, the functional grouping principle and the frequency of use grouping principles provide contradictory recommendations.

When the designer of a complex visual display is faced with contradictory recommendations from competing principles of information grouping, the research literature provides little guidance as to the relative importance of each grouping principle (Banks et al., 1983; Statler, 1984). As a result, the display designer is left with no specific recommendation for grouping information, and the designer must solve the problem of how to integrate information according to the dictates of intuition or guesswork (Wherry, 1984). In sum, the overwhelming problem with information integration is that there currently is no consensus on what the basis for grouping information should be, and there is little evidence as to the relative importance of the various grouping principles that have been suggested (Bishu & Drury, 1986; Schmidt, 1982; 1984).

Once a display designer decides to adopt a specific principle of information grouping, the problem of how to integrate information is not resolved completely. The designer of a complex display still must decide the degree to which information must be related before it should be combined or integrated. Although it generally is agreed that only correlated information should be combined, the specific degree of correlation that is required in order for integration to benefit, rather than degrade, performance has not been defined. Some authors suggest that the integration of moderately to highly correlated information will enhance operator performance. However, the specific value that denotes a moderate or a high correlation coefficient is left to the discretion of the designer or researcher (Benbasat & Taylor, 1982; Carswell & Wickens, 1984a).

The varying nature of the relationships between specific pieces of information may pose further problems for the design of effective displays. While two sets of information may display the same degree of correlation, the direction of the correlational relationship may be divergent. If both positive and negative correlations exist within a set of related data, there are no guidelines to determine whether both positively and negatively related information should be grouped together and, if so, whether the divergent direction of specific relationships should be identified to the observer by some sort of coding mechanism (Miles, Miller, & Varlakojis, 1982).

The complex interrelationships between the readings on a primary flight display serve as an excellent example of the problems encountered when attempting to display related information in an optimal manner. Generally, indications of the aircraft's airspeed, flight altitude, and attitude (e.g., whether the nose of the plane is pointing up or down) are presented in close proximity on the primary flight display. Although airspeed, altitude, and attitude readings are interrelated, the direction of the relationships among subsets of these variables is not constant. Increasing the attitude of a plane (e.g., bringing up the nose) causes altitude to increase. Thus, attitude and altitude demonstrate a positive relationship. However, the relationship between attitude and airspeed is negative; increasing the aircraft's attitude causes airspeed to decrease. Because changes in attitude drive altitude changes, altitude and airspeed also are related negatively, although this relationship is less direct than is the relationship between attitude and airspeed.

Considering the disparate direction of specific relationships among an aircraft's attitude, altitude, and airspeed readings, how should these variables be presented on the face of an integrated display? For example, traditional human factors guidelines specify that scale orientation should be consistent across adjacent instruments (Chapanis, 1969; Meister, 1985; Woodson, 1981). The guidelines also recommend that increases in the value of a reading on a vertical scale should be indicated by movement of the scale pointer from a lower to a higher position (McCormick & Sanders, 1981; Woodson & Conover, 1956). If these suggestions are followed, an increase in attitude and a decrease in airspeed are represented by movement of the two scale pointers in opposite directions (e.g., up for attitude, down for airspeed). Thus, the negative relationship between airspeed and attitude is underscored by the divergent direction of pointer movement on the airspeed and altitude indicators (Miles et al., 1982).

In spite of the argument outlined above, Miles et al. (1982) suggest that the scale orientation of vertical airspeed indicators should be reversed so that the lowest airspeed value is displayed at the top of the airspeed scale, while the highest airspeed value is represented at the bottom of the airspeed scale. In this scheme, both increases in altitude and decreases in airspeed are indicated by an upward movement of a scale pointer. The suggestion of a reversed scale for the airspeed indicator was stimulated by the comments of experienced pilots who reported that opposing scale pointer movement across airspeed and altitude instruments often was interpreted to mean than an aircraft had begun a horizontal roll. Thus, it may be that the opposing movement of airspeed and altitude scale pointers erroneously activated pilots' mental model of horizontal roll conditions more often that it highlighted a negative relationship airspeed and altitude readings. While this issue requires further investigation before firm recommendations can be made, it does illustrate the type of unsolved problems that are encountered in the design of integrated displays.

Task Type. Paradoxical findings from evaluations of integrated displays also have been attributed to the moderating effect of task type. Peterson, Smith, Banks, and Gertman (1982) reported that, in a stimulus detection task, functionally integrated displays improved performance over performance obtained with either traditional electro-mechanical displays, or with digital displays. However, these authors reported that performance in a stimulus location task was superior for subjects who viewed traditional electro-mechanical (e.g., nonintegrated) displays. These findings were replicated by Carswell and Wickens (1984b), Wickens et al., (1985), and by Boles and Bagnara (1986). Casey et al., (1984) reported that, while integrated displays improved performance on a signal detection task, RTs were longer and accuracy rates were lower for integrated displays than for electro-mechanical displays when subjects completed a fault detection task. Similar findings were reported by Coury, Boulette, Zubritcky, & Fisher (1980), Harwood, Wickens, Kramer, Clay, & Liu (1986), and by Schmidt (1982; 1984).

Information Format. The moderating effect of task type on information integration has been explained in terms of the varying levels at which information is integrated across studies (Calhoun & Herron, 1981; Schmidt, 1984). In this context, "levels of information integration" refers to the information format that is selected to display the results of the mechanical integration process. Levels of information integration exist on a continuum, with digital displays representing the low end of the integration continuum, pictorial displays representing abstract or highly integrated information, and electromechancial displays representing the midpoint on the continuum of information integration (Hunt, 1983; Schmidt, 1982).

Reduction of mental workload in the cockpit requires that information be displayed at the level of integration (e.g., data format) that enhances the observer's comprehension of the information's meaning. However, the optimal level of information integration appears to vary, depending on the task that the system operator is required to perform (Companion & Sexton, 1982; Garner & Felfoldy, 1970; Koonce et al., 1985; Wickens, 1984b).

When an operator needs to determine the exact value of a variable, quantitative information allows the operator to use the relatively slow but highly accurate serial processing mechanism to encode information (Holstein, 1974; Jacob, Egeth, & Bevan, 1976). Thus, if an operator needs to extract precise information, alphanumeric data that are displayed on a digital display will provide the information most accurately. Analogue or pictorial displays tend to evoke holistic or global information processing. This information processing strategy employs the "chunking" of information. Thus, it is more rapid but less accurate than serial information processing (Jacob et al., 1976; Posner & Mitchell, 1967; Snodgrass, 1972). When analogue or pictorial displays are used to obtain readings of a precise value, operators generally emit slow and inaccurate responses. This is due to the fact that the system operator must interpolate discrete pieces of information from an integrated display (Coury et al., 1986; Huntoon, 1983). In effect, the system operator must dismantle mentally the mechanical integration that was used to create the analogue or pictorial display (Goldsmith & Schvaneveldt, 1984; Huchingson, 1981).

While analogue and pictorial displays do not provide ready access to precise data values, they do enhance the perception of relationships between information, and they provide a rapid global overview of total system state (Carel, 1965; Holstein, 1974; Simon & Roscoe, 1956). Thus, for tasks that require the rapid observation of trends or the determination of rates of change, analogue and pictorial displays are particularly useful (Jacob et al., 1976; Koonce et al., 1985). Conversely, information formats that represent low levels of information integration (e.g. digital displays) are less useful for these objectives because they require the operator to integrate discrete pieces of related information in order to achieve task objectives (Caraux & Wanner, 1979; Grossman, 1983; Huntoon, 1983; Miles et al., 1982).

Most tasks that are performed in an operational environment require both the determination of discrete data values and the rapid estimation of overall system state. This fact has stimulated some human factors practitioners to recommend that operators of complex systems be provided with both integrated and nonintegrated information about each aspect of system functioning (Koonce & Moroze, 1982; Murphy & Mitchell, 1986). Theoretically, this practice would allow operators to select the data format that is most harmonious with the task at hand (Boles & Wickens, 1987). For example, during take-off and landing operations, it is necessary for a pilot to be advised of his or her precise altitude. However, during other phases of flight, it is necessary only for the pilot to maintain altitude within a specified range. A digital display most efficiently provides the specific information that a pilot needs to hold a precise attitude. However, an analogue display is likely to provide the most rapid comprehension of whether or not the current altitude reading is within specified limits.

The recommendation to provide information in both integrated and nonintegrated form has received support in the literature. For a task that involved monitoring critical parameters of flight, McGee and Harper (1982) reported that performance obtained with a combined analogue and digital display was superior to performance obtained with either a purely analogue (e.g., integrated), or a purely digital (e.g., nonintegrated) display. Combined digital and analogue displays also were found to improve performance on a system status monitoring task over performance obtained with strictly digital or strictly analogue displays (Chorley, 1984; DeMaio, Harman, Strybel, Penner, & Brock, 1985; Holmes, 1983). While these findings are encouraging, further research is required to replicate these study findings and to identify additional variables that moderate the effects of information format on air crew performance.

Principles of Display Design - Applied Problems

The preceding discussion illustrates the fact that the question of how best to present extensive amounts of information to operators of complex systems largely remains unanswered (Grossman, 1983; Morrison, 1986). Although techniques for the removal of display clutter have been suggested, and guidelines for the integration of information have been published, these recommendations generally are global and nonspecific. To date, few concrete recommendations have been generated that designers can adapt to their daily work.

The lack of specific principles for the design of complex visual displays is due largely to the fact that display technology has developed rapidly, while the understanding of human information processing has progressed more slowly (Grossman, 1983; Leffler, 1982; Morrison, 1986). While the adaptation of electronic display devices to the cockpit environment has provided increased flexibility to designers of cockpit displays, the knowledge of how best to use this flexibility has been elusive (Hollister, 1983; Hunt, 1983; Schmidt, 1984). The current lack of design principles that are directed specifically to the optimal utilization of electronic display technology is of concern.

If the design of electronic displays is not based on empirically tested principles of human information processing, the new flexibility provided by this technology may degrade rather than to enhance performance (Boles & Bagnara, 1986; Grossman, 1983; Morrison, 1986).

Even when guidelines for the design of visual displays are developed and tested, display designers often have a difficult time employing them. This is due, in part, to the conflicting nature of many principles of design for complex visual displays. Often display designers find that adherence to one principle of design means violating a related guideline. Of course, the logical course for the designer to follow in such a situation is to adhere to the design principle that has the greatest impact upon operator performance, even if doing so violates a related, but less influential, guideline. Unfortunately, this plan currently cannot be implemented, because there is no consensus as to the relative impact on performance of the various principles of display design.

One reason for the dearth of information about the relative importance of various design principles can be traced to the methods that were employed to derive the existing guidelines. Most of the data on which current design principles are based were obtained in experiments that explored the univariate relationship between a specific parameter of display design and performance quality (Sulzer, 1981; Wherry, 1984). Although the establishment of univariate relationships is important, this approach does not allow researchers to evaluate the relative importance of various factors to the successful design of complex visual displays. The establishment of univariate relationships also does not allow researchers to observe important interactions between design variables (Chapanis, 1969).

Overview/Hypotheses

Multivariate relationships between several parameters of display design and operator performance must be explored if principles of display design are to be characterized by good external validity (Wherry, 1984). With the advent of electronic visual displays, the evaluation of the relative effects of information density, principles of information integration, and information format on air crew performance appears to be a critical research need (Roscoe, 1968; Wherry, 1984). Therefore, the purpose of the current study was to evaluate the main and interactive effects of information density (low, medium, and high), information format (analogue, digital, and combined analogue and digital), and the principle by which information is grouped (sequential vs. functional) on operator performance in a complex, system monitoring task. In addition, the possible effects of task type and of orientation of the airspeed scale on the main and interactive effects of these variables were evaluated.

The following hypotheses were investigated in the current study:

1. Response time increases and response accuracy decreases as the level of information density increases.

2. Tasks that require subjects to consider only the value of an instrument reading in isolation are completed more rapidly and more accurately than are tasks that require subjects to consider an instrument reading in relation to other system state information.

3. For tasks that require subjects to consider only the value of an instrument reading in isolation, digital displays provide superior performance in terms of speed and accuracy of performance.

4. For tasks in which subjects are required to consider trend information, and for tasks in which subjects are asked to consider instrument readings in relation to other system state information, analogue displays provide superior performance in terms of speed and accuracy of performance.

5. For tasks in which subjects are required both to consider the specific value of an instrument reading, and to consider an instrument reading in relation to other system

state variables, combined analogue and digital displays provide superior performance in terms of speed and accuracy.

6. Reversing the orientation of the airspeed scale degrades performance across all conditions. However, for tasks that require subjects to consider the relationship between instrument readings, reversing the orientation of the airspeed scale degrades performance more severely than does reversing the airspeed scale orientation in tasks that require subjects to consider only the reading of each instrument in isolation.

7. The principle by which information is grouped moderates performance for tasks that require subjects to consider the relationship between instrument readings, but does not moderate performance in tasks that require only that the subject consider each instrument reading in isolation. For the former task type, grouping information according to the functional grouping principle provides superior performance in terms of speed and accuracy. This is due to the fact that functional grouping stresses the relationships between the readings on each of the three display instruments, while sequential grouping reflects only the order in which pilots often attend to specific instrument readings.

The hypotheses were expected to be supported by several significant experimental effects. A significant main effect for information density was predicted. Specifically, low information density was expected to provide the most rapid and accurate responses. It also was predicted that response time would increase and accuracy would decrease as the level of information density increased.

A significant information format by task type interaction was predicted in which the digital display format would provide faster and more accurate responses when subjects were asked to consider individual instrument readings in isolation. For tasks in which subjects were required to consider the relationships between instrument readings, analogue displays were expected to provide the most rapid and accurate responses. Finally, for tasks in which subjects were required to consider both discrete instrument readings and the relationship between instrument readings, the analogue and digital display format was expected to provide the most rapid and accurate responses.

A significant effect for task type by airspeed scale orientation also was predicted. When the airspeed scale orientation was the same as the orientation of the attitude and altitude scales, response time and accuracy were predicted to be better than when the airspeed scale orientation was the reverse of that for the attitude and altitude indicators. However, the reversed orientation of the airspeed indicator was expected to degrade performance significantly more when subjects were required to attend to the relationship between airspeed, attitude, and altitude indicator readings, than when the readings from these three instruments could be considered in isolation.

The effect of the grouping principle variable was expected to be moderated by task type. This hypothesis was expected to be confirmed in a significant interaction between grouping principle and task type. For tasks in which subjects are required to consider only the readings of each instrument in isolation, sequential and functional levels of the grouping principle were not expected to produce RT or percent correct response that is significantly different. However, for tasks in which the subject is required to attend to the relationship between the three instrument readings, functional grouping was expected to provide shorter RT and higher percent correct response than would the sequential level of the grouping principle.

Due to the relatively large number of subjects that were required by the experimental design of the current study, non-pilots were employed as subjects. This decision was supported by studies published by Koonce, Gold, and Moroze (1985) and by Rinalducci, DeMaio, Patterson, and Brooks (1983). Both sets of authors investigated the potential differences in performance between pilots and non-pilots in an aircraft system state monitoring task. The results of both studies indicated that pilots were faster and more accurate in their judgments of system state than were their non-pilot counterparts. However, data obtained from pilots and from non-pilots demonstrated no difference in the rankings of the effectiveness of various display parameters. Thus, while non-pilots were slower to respond, and were likely to make more errors than were their pilot subject counterparts, non-pilot subjects provided results that were externally valid when employed to determine the relative effectiveness of various principles of display design.

Method

Design

The experimental design was a factorial combination of two levels of Grouping Principle (Functional, Sequential), two levels of Airspeed Scale Orientation (Matching, Not matching), three levels of Information Format (Analogue, Digital, Combined Analogue and Digital), three levels of Information Density (Low, Medium, High), and three levels of Task Type (Current State Estimation, Future State Estimation, Combined Current and Future State Estimation). Information density, information format, and task type were within-subject variables, while grouping principle and airspeed scale orientation were between-subject variables.

Subjects

The subjects were eight graduate and 40 undergraduate students at Old Dominion University. All graduate students and approximately 85% of the undergraduate students were paid to participate in the current research. The remaining subjects were awarded course credit for research participation. Four subject groups were created, each of which contained nine males and nine females. All subjects were right handed predominantly, and each subject possessed uncorrected or corrected 20/20 vision, as tested by an American Optical Corporation Sight-Screener. No subject had received flight training or had experience piloting any type of aircraft.

Apparatus

The stimulus displays each provided readings from three flight instruments: 1) an attitude indicator; 2) an altitude indicator; and 3) an airspeed indicator. The stimulus displays were software generated and were presented to subjects on a NEC Multisync color computer monitor. The display software employed an EGA color card that provided a resolution of 640 x 350 pixels. Reflectance and chromatic contrast of the display elements and the display background were held constant across all experimental conditions and across all subjects. Ambient illumination in the experimental laboratory also was held constant across all experimental trials.

Subjects viewed the stimulus displays while seated approximately 39 cm from the stimulus display screen. Responses to the stimulus displays were signaled when a subject pressed three of six possible response keys on the computer keyboard. Response time was defined as the difference between the time at which the stimulus display appeared on the computer monitor (e.g., display time) and the time at which the subject had signaled a response to all three instruments on the stimulus display. Subject responses were recorded to the nearest millisecond by the computer's internal clock, and the order in which subjects responded to each of the three stimulus instruments also was recorded.

Stimulus Materials

A unique stimulus display was created for each possible combination of grouping principle, information format, and information density. This procedure resulted in a set of 18 unique display configurations. The 18 display configurations are illustrated in Figures 1 through 18 in Appendix A. In addition, a precise description of each display configuration, and the measurements for components within the displays, are provided in Appendix B.

Grouping Principle. Nine of the 18 display configurations represented sequential grouping while the remaining nine configurations represented functional grouping. For displays with sequential grouping, the attitude reading was located centrally on the display, with the airspeed reading on the left, and the altitude reading on the right, of the attitude reading. This arrangement of instrument readings was based on studies of pilot scanning behavior (Edwards, Tolin, & Jonsen, 1982; Harris & Spady, 1985; Pennington, 1982). Such studies have demonstrated that pilots direct their visual scan toward the attitude indicator most often. Thus, the attitude indicator serves as a "home base" for the pilots point of visual regard.

When a pilot directs his or her visual scan away from the attitude indicator, just one additional instrument generally is scanned before the pilot's gaze is directed back to the attitude indicator (Harris & Spady, 1985; Pennington, 1982; Tole, et al., 1983). In light of these data, proponents of sequential grouping recommend that the attitude indicator be located centrally on a display, while instruments to which the pilot often shifts his or her gaze from the attitude indicator are placed in close proximity to the attitude indicator.

For display configurations representing functional grouping, the attitude reading was displayed along the left boundary of the display. The altimeter reading was positioned to the near right of the attitude reading, while the airspeed reading was positioned to the far right of the altitude reading. This arrangement of flight instruments was based on the fact that the relationship between readings on the attitude and altitude indicators is functional, while the relationship between airspeed and the remaining instrument readings is incidental. For example, pilots change the attitude setting in a direct attempt to change the altitude at which the aircraft is flying. However, pilots do not manipulate attitude in order to alter airspeed. Rather, the change in airspeed that accompanies a change in attitude is an undesired side effect to which a pilot must respond. Thus, according to the functional grouping principle, attitude and altitude should be grouped together, while airspeed should be presented in a distinct, but spatially proximate, area of the flight display.

Information Format. For each level of grouping principle, a display configuration was created for each level of information format. Thus, for each sequentially grouped, and for each functionally grouped display, a digital, an analogue, and a combined analogue and digital configuration was created. Digital displays consisted of three equally spaced digital readouts, with each readout representing one of the three instrument readings (altitude, attitude, or airspeed).

Analogue airspeed and altitude readings were characterized by a fixed scale and a moving pointer. The two vertical scales were drawn in white against a dark green background. The attitude indicator consisted of nine vertically spaced "hash marks" that were presented against a dual color background. The top half of this background area was blue, while the bottom half of the background area was brown. These background colors matched the standard sky/earth colors that often are used to signify positive and negative attitude, respectively. The boundary between the two background colors signified a neutral attitude reading. The top edge of a small airplane symbol served as the scale pointer for the attitude indicator. Unlike the scales for altitude and airspeed, the analogue attitude indicator was characterized by a moving scale and fixed pointer.

On the combined analogue and digital displays, instrument readings were displayed in analogue form. However, a digital reading was printed beside the analogue scale pointers. The digital readings matched the value signified by the position of the analogue scale pointer. On the airspeed and altitude scales, the digital reading was placed on the outside edge of the analogue scale pointer, while the digital reading was placed between the two legs of the airplane symbol on the attitude indicator. All digital readouts were identical in size and shape to the digital readouts used in the digital display configurations.

Information Density. Displays representing each of the three levels of information density were created for each possible combination of grouping principle and information format. For the digital information format, low information density was represented by the display of one digital readout for each of the three stimulus instruments. Medium information density was created by the addition of one digital distractor reading above, and one distractor reading below, the stimulus readout. High information density was created by the addition of two distractor readings above, and two distractor readings below, the stimulus readout.

For analogue displays, low information density was created by adding no distractor symbols to the altitude, airspeed, or attitude scales. Medium information density was created by adding two graphic distractor symbols to the presentation area of each instrument, while high information density was created by adding four graphic symbols to the presentation area of each stimulus instrument.

Low information density for the combined analogue and digital configurations was created by adding no distractor symbols to the attitude, altitude, and airspeed indicators. Medium and high information density was created by a procedure that was similar to the procedure described for creating medium and high information density for the purely analogue displays. However, for the combined analogue and digital displays, supplemental cues for each level of information density were evenly divided between alphanumeric and graphic distractor symbols.

Orientation of the Airspeed Scale. For analogue, and for combined analogue and digital displays, a unique display configuration was created for each level of orientation of the airspeed scale. For conditions in which the orientation of the airspeed scale matched the orientation of the attitude and altitude indicators, low airspeed values were signified when the airspeed scale pointer was positioned toward the bottom of the airspeed scale, while high airspeed values were signified when the scale pointer was positioned toward the top of the airspeed scale. For not matching airspeed scale conditions, low airspeed values were signified when the scale pointer was positioned toward the top of the airspeed scale, while high airspeed values were represented when the scale pointer was positioned toward the bottom of the airspeed scale.

Instrument Readings

Seventeen possible instrument readings were created for each of the three stimulus instruments (see Appendix C). The correct or incorrect identity of each instrument reading was determined by the level of task type in which the subject responded.

In the current state estimation task, subjects were required to determine whether or not each of the three instrument readings was within prespecified flight limits. The prespecified flight limits indicated that attitude should be between +02 and -02 degrees, altitude should be between 200 and 300 ft, and airspeed should be between 80 and 120 kt. Three of the 17 possible readings for each instrument represented correct values (e.g., within prespecified limits), while the remaining instrument readings represented incorrect instrument readings for the current state estimation task.

Fifty-four combinations of readings across the three stimulus instruments were created for the current state estimation task (see Appendix D). Of these 54 sets of instrument reading, 27 represented correct readings for all three instruments, while the remaining 27 combinations provided one or more incorrect instruments readings. Nine of the 27 incorrect displays presented an incorrect reading on one instrument only. Of these nine displays, three incorrect readings were presented on each of the three stimulus instruments. Nine of the incorrect displays presented an incorrect reading on two instruments. Of these incorrect instrument readings, three were provided by the altitude and attitude indicators, three were provided by the attitude and airspeed indicators, and three were provided by the airspeed and altitude indicators. The remaining incorrect displays presented incorrect instrument readings on all three stimulus instruments.

In the future state estimation task, subjects were required to decide whether the combination of instrument readings in a flight display would preserve or return the aircraft to prespecified flight conditions. Thus, a single instrument reading could not be identified as correct or as incorrect without considering the readings on the remaining instruments in the stimulus display. For example, attitude may have been low because altitude was too high, and airspeed was too low. The negative attitude setting would reduce altitude and would increase airspeed. As a result, a negative attitude reading, in combination with high altitude and low airspeed, would require a response of "correct" for each of the three instruments. Thus, subjects had to consider the relationships between the readings on the three stimulus instruments in order to determine the correct or incorrect identity of a specific instrument reading.

Due to the fact that correct and incorrect readings for each instrument were defined by a combination of instrument values, the number of correct and incorrect values for specific instrument readings could not be determined for the future state estimation task.

A separate set of 54 combinations of three instrument readings was created for use in the future state estimation task (see Appendix E). As in the current task stimulus set, 27 of the future task displays represented correct readings, while the remaining 27 displays provided incorrect readings on one or more instruments. However, in the future task stimulus set, the set of correct displays included 13 displays with correct readings on all three instruments, seven displays with high attitude in combination with high airspeed and low altitude, and seven displays with low attitude in combination with low airspeed and high altitude. The set of incorrect displays for the future state estimation task included 14 displays with one incorrect instrument reading. Seven of these displays provided an incorrect altitude reading, while the remaining 7 displays presented an incorrect airspeed reading. The remaining thirteen displays with incorrect instruments readings presented an incorrect reading on each of the three instruments.

In the dual task condition, both current state estimation and future state estimation were completed for each stimulus display. Thus, a response measure for both current and for future state estimation was recorded in the dual task condition. As a result, single task estimates and dual task estimates were obtained for current and for future state estimation.

A third set of combined instrument readings was created for the dual task condition (see Appendix F). This stimulus set was comprised of 54 combinations of instrument readings that were selected randomly from the current task stimulus set and from the future task stimulus set. Random selection was conducted according to the constraint that 13 correct and 14 incorrect displays would be selected from the current task stimulus set, while fourteen correct and 13 incorrect displays would be drawn from the future task stimulus set.

Of the 14 incorrect displays from the current task stimulus set, four represented one incorrect instrument reading. As a result of the random selection, the airspeed and attitude indicators each provided one incorrect reading, while the altitude indicator represented two of the incorrect instrument readings. Five of the incorrect displays from the current task set represented two incorrect instrument readings. Among these five displays, two represented incorrect readings on the attitude and altitude indicators, two provided incorrect readings on the attitude and airspeed scales, and one represented incorrect readings on the altitude and airspeed scales. The remaining five incorrect displays from the current task set provided incorrect readings on each of the three stimulus instruments.

The correct displays selected from the future task set included four displays with correct readings on all three instruments, five displays with high altitude in combination with high airspeed and low attitude, and five displays that provided low altitude in combination with low airspeed and high attitude. The 13 incorrect displays that were drawn from the future task stimulus set included eight displays with incorrect readings for one instrument. Four of these displays provided incorrect airspeed readings, while the remainder provided incorrect altitude readings. Finally, five displays drawn from the future task stimulus set provided incorrect readings on each of the three stimulus instruments.

Sets of Experimental Trials

Twenty-seven sets of 28 stimulus trials (24 experimental, 4 practice) were created for a total of 648 experimental trials, 108 practice trials, and 756 total trials. Each set of experimental trials contained two correct and two incorrect practice trials as well as 12 correct and 12 incorrect experimental trials. One combination of task type, information format, and information density was tested with each set of stimulus trials.

Values for display in each set of experimental trials were selected randomly from the appropriate list of instrument reading combinations. Random selection proceeded according to the restrictions that: 1) 14 correct and 14 incorrect stimulus displays would be presented in each set of 28 stimulus trials; 2) two correct and two incorrect displays would be included in each set of four practice trials; 3) each specific combination of instrument readings would be presented only once in each stimulus set; and 4) no more than three correct or three incorrect stimulus trials would be presented in succession.

Procedure

Twelve subjects (six male; six female) viewed the stimulus displays in each grouping principle by scale direction condition. Subjects were tested individually in a single three-hour session. Upon arrival, the subject's visual acuity was tested and the experimental procedure was explained to the subject. A consent form then was signed by the subject.

A 20 minute training session was provided to each subject (See Appendix G). Training diagrams that provided various combinations of airspeed, attitude, and altitude readings were used to enhance the training process. During the training session, the meaning of aircraft altitude, airspeed, and attitude were explained. Subjects then were shown how to read the attitude, airspeed, and altitude scales. The current state estimation task then was explained to the subject. At this point in the training session, the subject was required to view four test displays and to determine whether or not each of the three instrument readings represented a correct or an incorrect reading. No subject committed an error on any of the four test displays for the current state estimation task.

The next phase of the training session was used to explain the future state estimation task. The relationships between altitude, airspeed, and attitude was defined, and several correct and incorrect sets of instrument readings were demonstrated to the subject. Subjects again were required to view two correct and two incorrect test displays, and to determine whether each of the three instrument readings in each test display represented a correct reading under conditions of future state estimation. In the event that a subject responded incorrectly to any instrument in the test displays, an explanation of the error was given, and instructions for future state estimation were reviewed. The subject then was asked to view four new test displays, and to determine the correct or incorrect identity of the instrument readings within the displays.

Once the subject had demonstrated that he or she understood the current and the future state estimation tasks, the displays configurations for analogue, digital, and combined analogue and digital displays were described briefly.

Finally, response key assignments were explained to the subject. For single task conditions, subjects were instructed to signal a response of "correct" or "incorrect" for <u>each</u> stimulus instrument by pressing one of two computer keys. Thus, for each task trial, three of six possible responses were to be signaled (e.g., "correct" or "incorrect" for airspeed, attitude, and altitude).

For single task conditions, subjects were instructed to rest the first, second, and third finger of their right hand on the "j," "k," and "l" keys of the computer keyboard, respectively. Half of the subjects in each grouping principle by scale direction condition signaled a response of "correct" by pressing the key directly above the resting position key, while signaling a response of "incorrect" by pressing the key directly below the resting key. The remaining subjects in each grouping principle by scale direction condition received the reverse response assignment.

Response assignments remained constant within subjects across all single task conditions. However, stimulus-response key association varied between subjects, depending upon whether the subject performed in the functional or in the sequential grouping condition. Subjects in the sequential grouping condition viewed a display that presented airspeed, attitude, and altitude instruments from left to right, respectively. Thus, the response keys that correspond to these specific instruments were positioned with airspeed, attitude, and altimeter response keys positioned from left to right. For functional grouping, attitude, altitude, and airspeed instruments were positioned from left to right, respectively. Thus, for subjects in the functional grouping condition, the attitude, altitude, and airspeed response keys were positioned from left to right.

In the dual task condition, subjects again were instructed to rest the first, second, and third finger of their right hand on the "j," "k," and "l" keys of the computer keyboard, respectively. However, in the dual task condition, subjects also were required to rest the corresponding fingers of their left hand on the "a," "s," and "d" keys of the computer keyboard. Subjects signaled "correct" responses in the same direction (e.g., up vs. down from resting key) that was employed in the single task conditions. However, within each conditions of up or down direction of response, half of the subjects in each grouping principle by airspeed scale orientation group signaled responses for the current task on the right side of the computer keyboard, while signaling responses for the future task were signaled on the left side of the computer keyboard. The remaining subjects received the reverse response assignment.

Before beginning the experimental trials, subjects were informed that accuracy of performance must be kept at the 95% level across all experimental conditions. Subjects were informed that, in order to obtain 95% accuracy, a mistake could be made on no more than four of the 84 instruments contained in each set of 28 stimulus displays. Within this level of accuracy, subjects were asked to respond as rapidly as possible. However, subjects were told not to sacrifice accuracy in order to increase their speed of response.

Each stimulus trial consisted of the presentation of one static stimulus display, and the registration of the subject's response to each instrument in the stimulus display. A stimulus display remained in view until the subject had responded to each of the instrument readings. When a response to each instrument had been made, the stimulus display disappeared from view. Following an interstimulus interval of 2.4 seconds, the next display appeared on the computer monitor.

The first four trials in each stimulus set were practice trials for which no response data were collected. Following presentation of the practice trials, subjects responded to the experimental stimuli. When a set of 28 stimulus trials had been completed, a message stating that the current block of trials was finished was displayed on the computer monitor. Before starting the next set of stimulus trials, the experimenter briefly described the display configuration to which the subject would be exposed next. The experimenter then restarted the stimulus trials by pressing a key on the computer keyboard. A rest period of five minutes was allowed after completion of each three sets of stimulus trials.

Each subject completed all trials in one level of task type before receiving the next level of task type. Half of the subjects completed the current task condition before receiving the future task condition, while the remaining subjects were subjected to the reverse task type presentation order. The dual task condition was presented to all subjects as the final task type condition. Within each level of task type, all trials of one level of information format were completed before the subject received the next level of information format. Within each level of information format, all trials of one level of information density were completed before the subject received the next level of information density.

Given the constraints imposed on stimulus presentation order, 72 stimulus presentation orders were possible under single task conditions, while 36 stimulus presentation orders were possible for the dual task condition. Stimulus presentation order was counterbalanced across subjects by randomly assigning each subject to a unique task type by information format by information density stimulus presentation order. For single task conditions, stimulus presentation order was assigned randomly from the list of 72 possible single task stimulus presentation orders. However, in each grouping principle by scale orientation condition, six subjects received the current state estimation task first, while the remaining six subjects received the future state estimation task first. Subjects were assigned randomly to one of the 36 possible information format by information density stimulus presentation orders for the dual task condition. Assignment to stimulus presentation order in the dual task condition proceeded according to the restriction that no subject would receive the same stimulus presentation order for single and dual task conditions, and according to the restriction that no more than two subjects would serve in each of the 36 possible stimulus presentation orders for dual task conditions.

Following completion of the nine sets of stimulus trials, subjects were debriefed orally. The study hypotheses were explained, and the expected findings were discussed. Results of the study were available to the subjects upon request.

Results

Mean median RT and mean percent correct response were obtained for each subject as a function of grouping principle (sequential, functional), orientation of airspeed scale (matching altitude and attitude, reversed from altitude and attitude), task type (single task current state estimation, single task future state estimation, dual task current state estimation, dual task future state estimation), information format (analogue, digital, combined analogue and digital), and information density (low, medium, high). Data were not discarded from the statistical analyses on the basis of response latency, or on the basis of percent correct response.

Identical five-factor mixed model analyses of variance were performed on the RT data, and on the percent correct response data. Information density, information format, and task type were within-subjects variables, while grouping principle and orientation of airspeed scale were between-subject factors. Newman-Keuls post hoc analyses were conducted for all significant main effects, while tests for simple effects were completed for each significant interaction. The analyses of variance for the RT and for the percent correct response are summarized in Tables 1 and 2, respectively.

Main Effects

As can be seen in Table 1, three main effects were significant for the RT data. RT for the matching airspeed scales was significantly shorter (*M* = 5501.3 ms) than RT for the reversed airspeed scales (*M* = 6860.2 ms). However, percent correct response was not significantly different between matching (83.9%) and reversed (81.8%) airspeed scales.

Insert Tables 1 and 2 about here

A main effect for task type is illustrated in Figure 1. As can be seen in Figure 1, RT was shorter for current state estimation than for future state estimation. This effect held across single and dual task conditions. However, performance in the dual task condition affected

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Insert Figure 1 about here

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current and future state estimation differently. RT for current state estimation was longer in dual task conditions than in single task conditions. Conversely, RT for future state estimation was longer in single task condition than

Table 1

Analysis of Variance Summary Table for Reaction Time Data

Source	df	Mean Square	F	Eta Square
Grouping Principle (GP)	1	33834928.47	0.21	
Scale Orientation (SC)	1	797783284.51	5.04*	.025
Task Type (TT)	3	2008543614.00	60.70*	.189
Information Format (IF)	2	535684552.00	32.49*	.034
Information Density (ID)	2	10457609.68	2.89	
GP x SC	1	199337460.31	1.26	
GP x TT	3	94212929.07	2.85*	.009
GP x IF	2	3499994.96	0.21	
GP x ID	2	8015356.78	2.22	
SC x TT	3	92771526.17	2.80*	.009
SC x IF	2	147222170.70	8.93*	.009
SC x ID	2	2886894.19	0.80	
TT x IF	6	204420990.00	17.08*	.039
TT x ID	6	3105706.46	0.94	
IF x ID	4	12104765.75	2.60*	.002
GP x SC x TT	3	37835394.70	1.14	
GP x SC x IF	2	2024052.61	0.12	
GP x SC x ID	2	9069424.12	2.51	
GP x TT x IF	6	7764122.61	0.65	
GP x TT x ID	6	3885351.77	1.18	
GP x IF x ID	4	2865613.91	0.61	
SC x IF x ID	4	17387872.69	3.73	.002
SC x TT x IF	6	58643803.30	4.90*	.011
SC x TT x ID	6	5293674.58	1.60	
TT x IF x ID	12	2048712.96	0.43	
GP x SC x TT x IF	6	7186901.75	0.60	
GP x SC x TT x ID	6	8756047.79	2.65*	.002
GP x SC x IF x ID	4	3465035.55	0.74	
GP x TT x IF x ID	12	6879914.16	1.43	
SC x TT x IF x ID	12	2911390.88	0.61	
GP x SC x TT x IF x ID	12	7489465.52	1.56	
Subject (GP*SC)	44	158177638.30		
TT*Subject (GP*SC)	132	33087109.18		
IF*Subject (GP*SC)	88	16485873.24		
ID*Subject (GP*SC)	88	3613029.23		
TT*IF*Subject (GP*SC)	264	11969579.27		
TT*ID*Subject (GP*SC)	264	3298585.01		
IF*ID*Subject (GP*SC)	176	4659575.99		
TT*IF*ID*Subject(GP*SC)	528	4809732.31		

*$p < .05$

Table 2

Analysis of Variance Summary Table for Percent Correct Response

Source	df	Mean Square	F	Eta Square
Grouping Principle (GP)	1	.23877	0.27	
Scale Orientation (SC)	1	.20003	0.22	
Task Type (TT)	3	1.24915	24.22*	.058
Information Format (IF)	2	.32892	16.01*	.010
Information Density (ID)	2	.00013	0.03	
GP x SC	1	.89073	0.99	
GP x TT	3	.14828	2.88*	.007
GP x IF	2	.01199	0.58	
GP x ID	2	.00963	2.26	
SC x TT	3	.65557	12.71*	.030
SC x IF	2	.17930	8.73*	.006
SC x ID	2	.01259	2.95	
TT x IF	6	.13029	12.12*	.012
TT x ID	6	.00177	0.58	
IF x ID	4	.00065	0.18	
GP x SC x TT	3	.05704	1.11	
GP x SC x IF	2	.01274	0.62	
GP x SC x ID	2	.00076	0.18	
GP x TT x IF	6	.00883	0.82	
GP x TT x ID	6	.00691	2.28*	.001
GP x IF x ID	4	.00976	2.65*	.001
SC x TT x IF	6	.05929	5.51*	.006
SC x TT x ID	6	.00150	0.50	
SC x IF x ID	4	.00343	0.93	
TT x IF x ID	12	.00330	1.16	
GP x SC x TT x IF	6	.01071	1.00	
GP x SC x TT x ID	6	.00172	0.57	
GP x SC x IF x ID	4	.00276	0.75	
GP x TT x IF x ID	12	.00282	1.00	
SC x TT x IF x ID	12	.00182	0.64	
GP x SC x TT x IF x ID	12	.00251	0.89	
Subject(GP*SC)	44	.90045		
TT*Subject(GP*SC)	132	.05157		
IF*Subject(GP*SC)	88	.02055		
ID*Subject(GP*SC)	88	.00427		
TT*IF*Subject(GP*SC)	264	.01075		

(Table Continued)

Source	df	Mean Square	F	Eta Square
TT*ID*Subject(GP*SC)	264	.00303		
IF*ID*Subject(GP*SC)	176	.00368		
TT*IF*ID*Subject(GP*SC)	528	.00283		

*$p < .05$

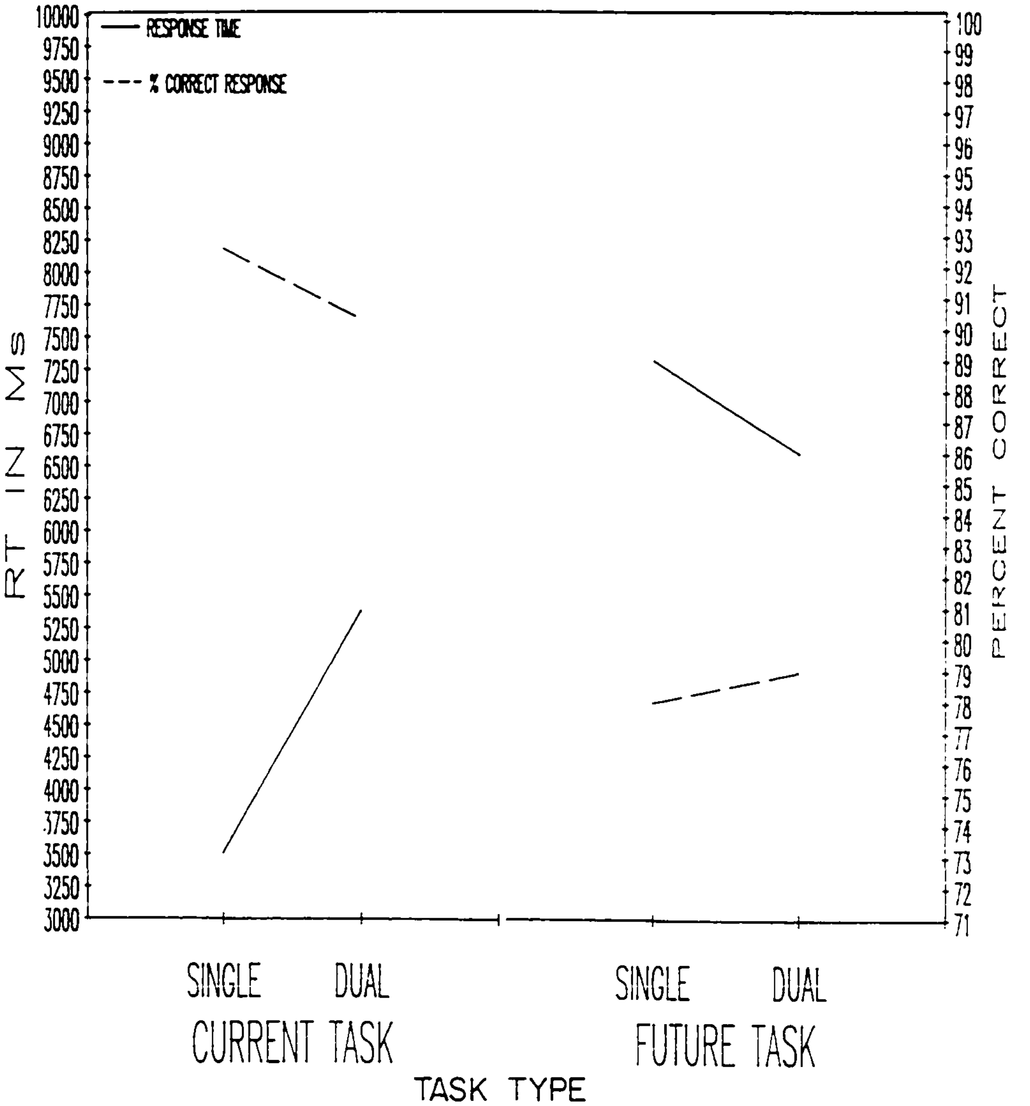

Figure 1. Mean Median RT and Mean Percent Correct Response for Task Type

in dual task conditions. A significant difference between each level of the task type variable was confirmed by the Newman-Keuls post hoc analysis.

A significant effect of task type also was obtained in the analysis of percent correct response. As can be seen in Figure 1, current state estimation was significantly more accurate than was future state estimation. Current state estimation was significantly more accurate in the single task condition than in the dual task condition. For future state estimation, percent correct response was not significantly different for single and dual task conditions.

A significant effect was obtained for the information format variable in the analysis of RT, and in the analysis of percent correct response. These data are illustrated in Figure 2. Responses for digital information format were slower, and less accurate, than were responses in any other

Insert Figure 2 about here

level of the information format variable. RT and percent correct response were not significantly different for analogue and combined analogue and digital information formats.

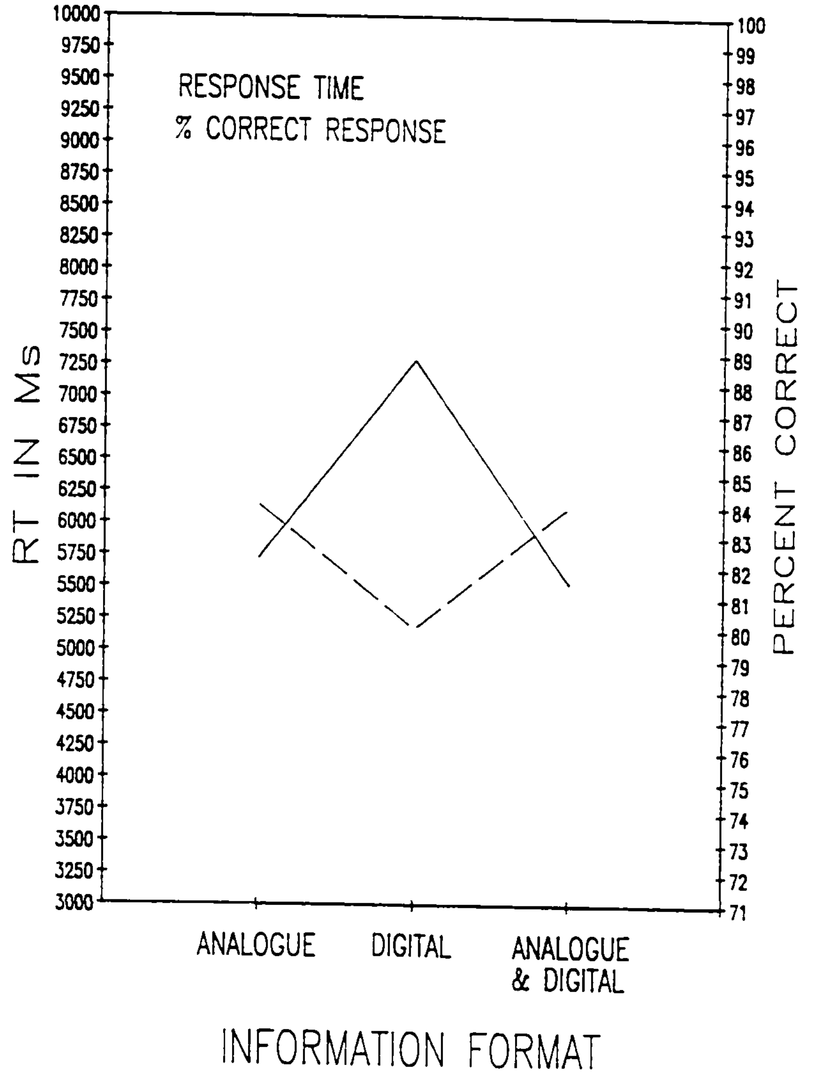

Figure 2. Mean Median RT and Mean Percent Correct for Information Format

The grouping principle variable did not significantly affect RT or percent correct response. Mean median RT for functional grouping was 6320.7 ms, while mean median RT for sequential grouping was 6040.8 ms. Percent correct response for functional grouping was 84.1%, while percent correct response for sequential grouping was 81.7%.

Information density also failed to moderate RT and percent correct response. RT for low, medium, and high information density was 6334.1 ms, 6126.9 ms, and 6081.3 ms, respectively. Percent correct response was 83% for each level of the information density variable.

Grouping Principle by Task Type Effects

A significant interaction between grouping principle and task type was obtained for RT, and for percent correct response. These data are illustrated in Figures 3 and 4, respectively. Neither RT nor percent correct response for the current state estimation task was moderated by the grouping principle variable. This effect held both for single and for dual task conditions.

In the single task condition, the effect of grouping principle on future task RT was moderated by task type. Under these conditions, RT was significantly shorter for sequential than for functional grouping. However, percent correct response for single task estimates of future system state was significantly lower for sequential than for functional grouping. For dual task estimates of future

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Insert Figures 3 and 4 about here

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system state, grouping principle moderated neither RT nor percent correct response.

Airspeed Scale Orientation by Information Format by Task Type Effects

The interaction between orientation of the airspeed scale, information format, and task type was significant in the analysis of RT. As can be seen in Figure 5, RT was significantly shorter for matching than for reversed airspeed scales, regardless of information format, and regardless of task type.

Insert Figure 5 about here

Orientation of the airspeed scale moderated the effect of information format on estimates of current system state. For matching airspeed scales, information format did not moderate RT for current state estimation, either in single or in dual task conditions. However, under reversed

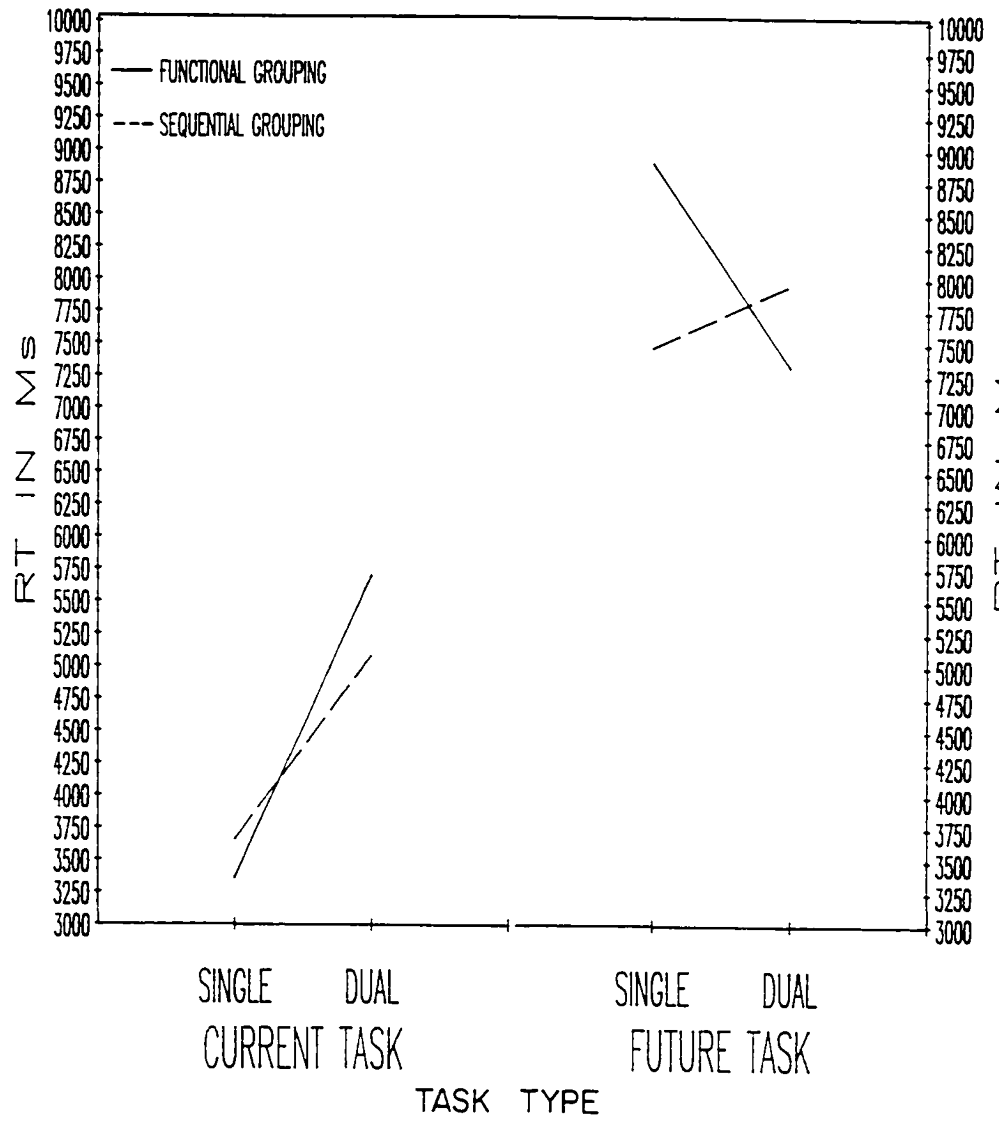

Figure 3. Mean Median RT for Grouping Principle by Task Type Format

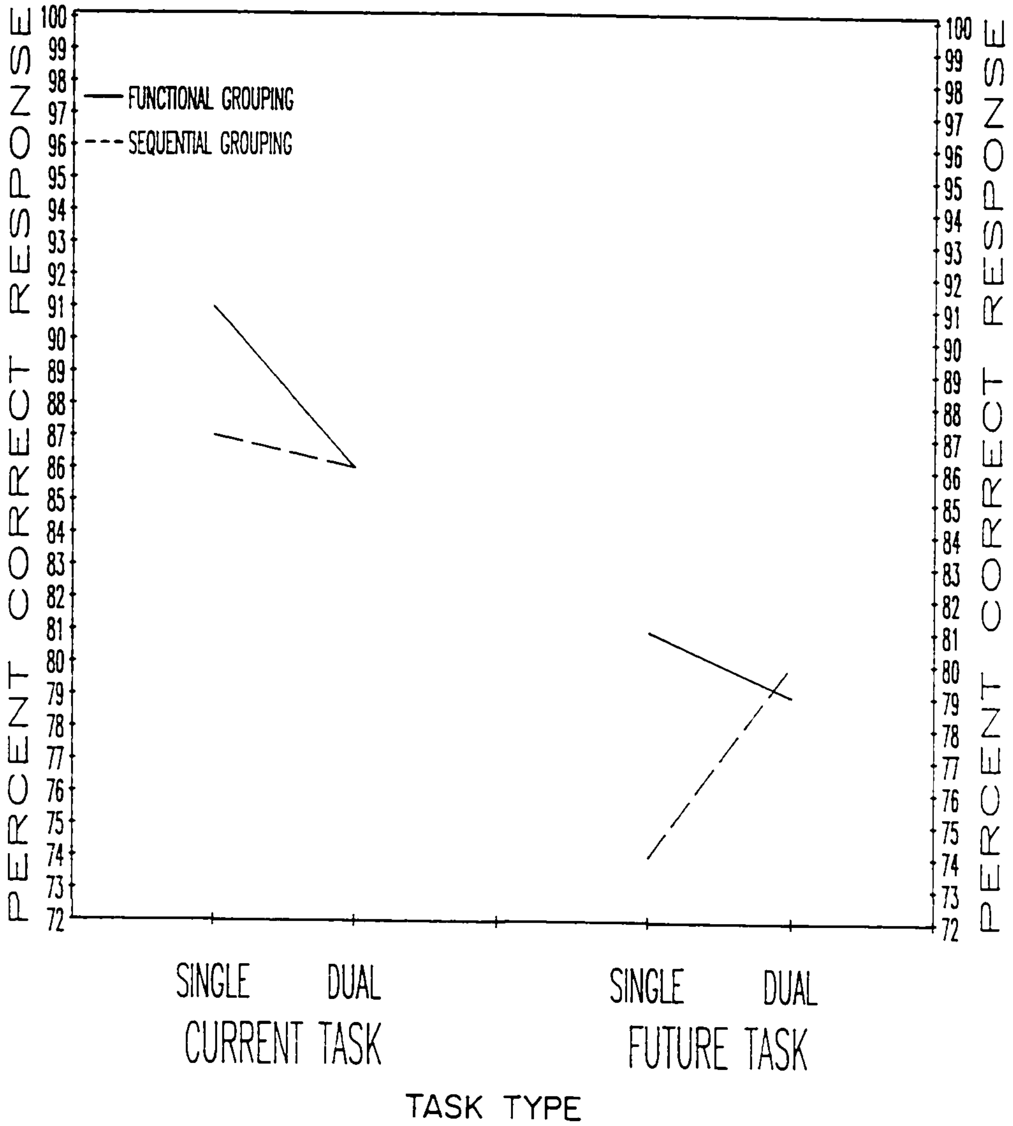

Figure 4. Mean Percent Correct Response for Grouping Principle by Task Type Effects

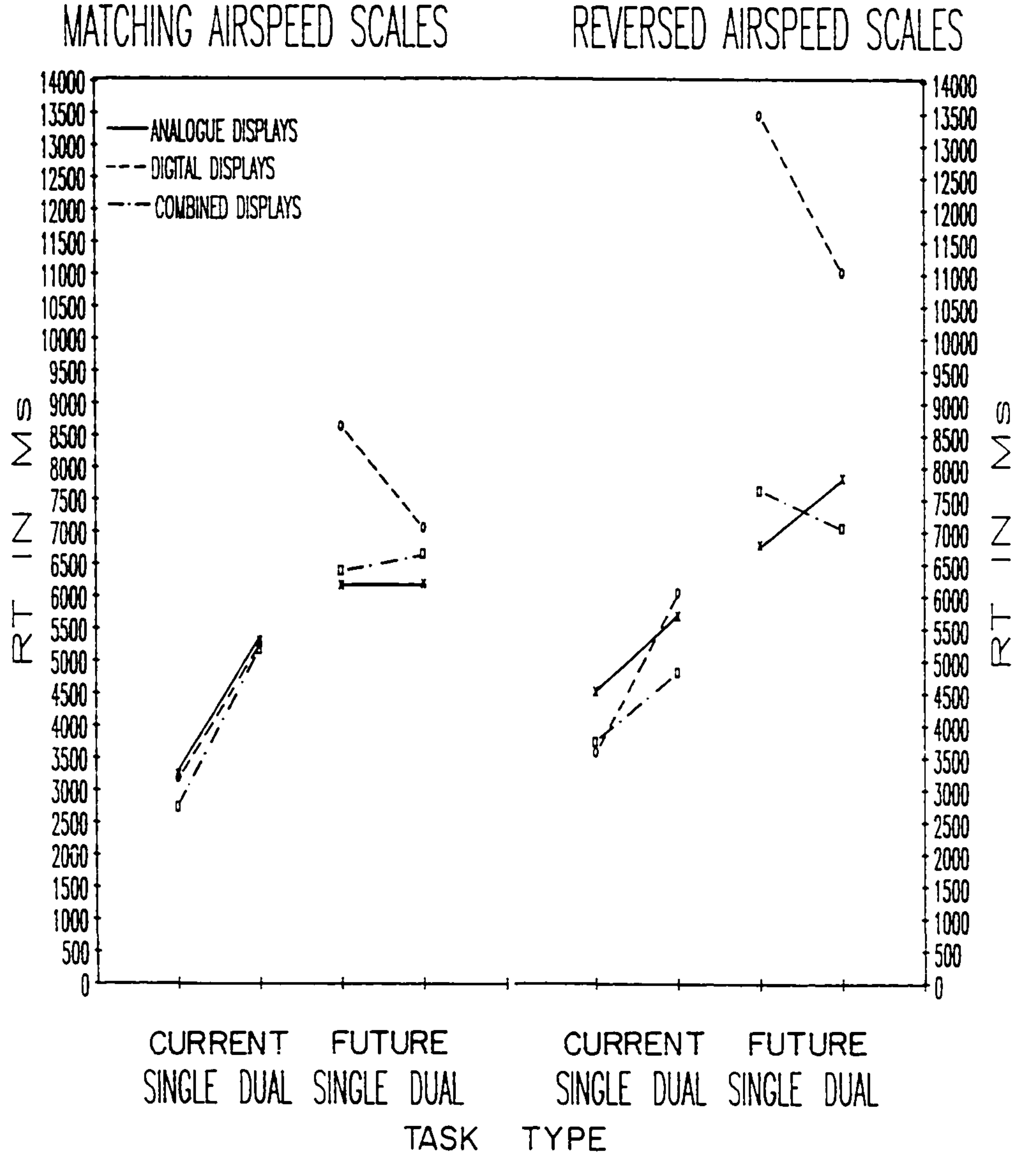

Figure 5. Mean Median RT for Airspeed Scale Orientation by Information Format by Task Type

airspeed scale conditions, RT for single task estimates of current system state were significantly longer for analogue displays than for either digital or combined analogue and digital displays. For dual task estimates of current system state, RT was significantly longer for analogue and for digital displays than for combined analogue and digital displays.

The orientation of the airspeed scale also moderated the effect of information format on estimates of future system state. For both matching and reversed airspeed scale conditions, RT was significantly longer for digital information format than for analogue or for combined analogue and digital information format. However, the detrimental effect of digital information format was greater for reversed than for matching airspeed scales. This effect held across single and dual task conditions of future state estimation.

Single task estimates of future system state were significantly faster for analogue displays than for combined analogue and digital displays. This effect held for both matching and for reversed orientations of the airspeed scale. However, in dual task conditions, the orientation of the airspeed scale moderated future task RT for analogue and for combined analogue and digital displays. Under matching airspeed scale conditions, RT was significantly faster for analogue displays than for combined analogue and digital displays. Conversely, under the reversed airspeed scale condition, RT was significantly faster for combined analogue and digital displays than for purely analogue displays.

A significant interaction between orientation of the airspeed scale, information format, and task type also was obtained in the analysis of percent correct response. These data are illustrated in Figure 6. Information format did not moderate the percent correct response for estimates of

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Insert Figure 6 about here

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current system state, either in single or in dual task conditions. However, under current task conditions, the task type variable moderated the effect of orientation of the airspeed scale on percent correct response. For dual task estimates of current system state, the percent correct response was significantly higher for reversed airspeed scales than for matching airspeed scales. However, for single task estimates of current system state, the percent correct response was not significantly different for matching and for reversed airspeed scales.

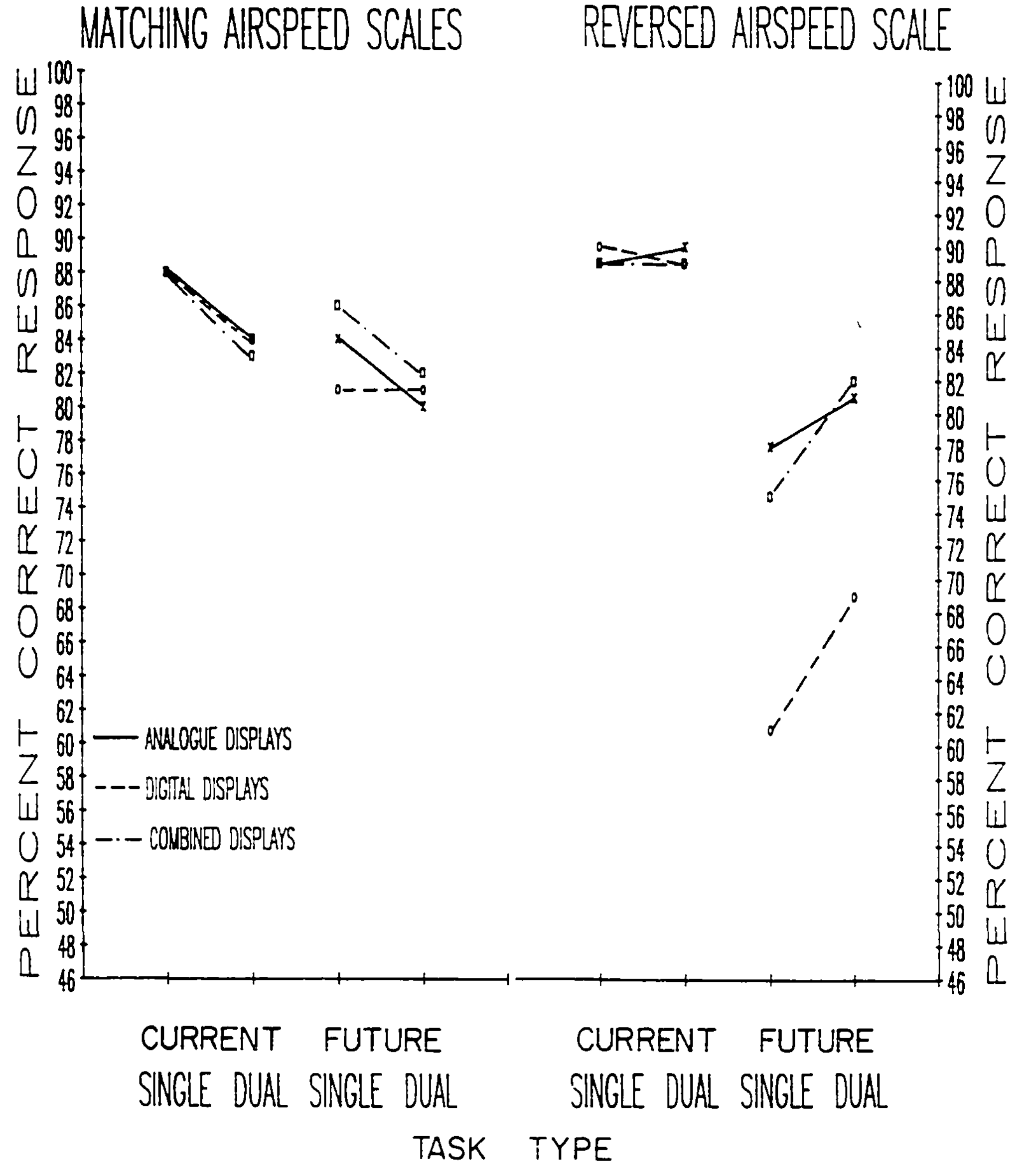

Figure 6. Percent Correct Response for Airspeed Scale Orientation by Information Format by Task Type

The percent correct response for future state estimation was significantly higher for matching than for reversed airspeed scale orientation. This effect was significant for both single and dual task conditions.

For single task estimates of future system state, the percent correct response was significantly lower for digital information format than for analogue information format, or for combined analogue and digital information format. This effect held across matching and reversed airspeed scale conditions. However, the detrimental effect of digital information was greater for reversed airspeed scales than for matching airspeed scales.

For single task estimates of future system state, the percent correct response for analogue displays, and for combined analogue and digital displays, was moderated by the orientation of the airspeed scale. For matching airspeed scales, percent correct response was significantly higher for combined analogue and digital displays than for analogue displays. However, for reversed airspeed scales, the percent correct response was higher for analogue displays than for combined analogue and digital displays.

The orientation of airspeed scale also moderated the effect of information format on percent correct response for dual task estimates of future system state. Under conditions of reversed airspeed scale, the percent correct response was significantly lower for digital information format than for the remaining levels of information format. However, percent correct response was not significantly different for analogue information format and combined analogue and digital information format, either in matching or reversed airspeed scale conditions.

Scale Type by Information Format by Information Density Effects

The interaction of orientation of the airspeed scale, information format, and information density was significant for RT, but was not significant for percent correct response. The RT data are illustrated in Figure 7. RT was significantly longer for digital information than for the remaining levels of information format. This effect was significant for both matching and for reversed airspeed scales at all levels of information density.

Insert Figure 7 about here

For matching airspeed scale conditions, RT was not significantly different between the analogue and the combined analogue and digital information formats at any level of information density. However, for conditions of

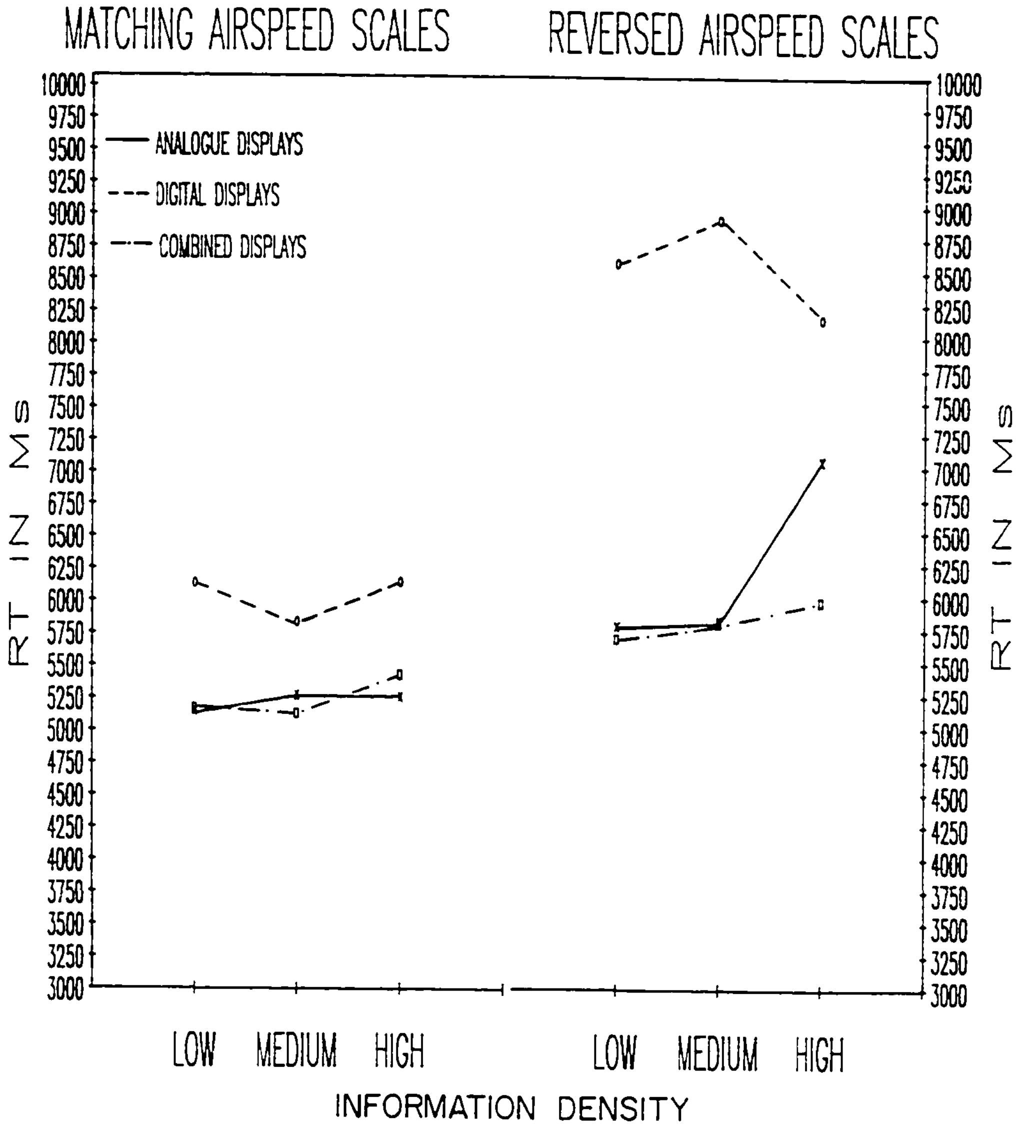

Figure 7. Mean Median RT for Airspeed Scale Orientation by Information Format by Information Density

reversed airspeed scale, the effect of information format was moderated by information density. RT was significantly shorter for combined analogue and digital displays than for purely analogue displays under conditions of high information density. Conversely, RT was not significantly different for analogue and combined analogue and digital displays in conditions of either low or medium information density.

Grouping Principle by Information Format by Information Density Effects

The interactive effect of grouping principle, information format, and information density significantly affected percent correct response, but did not significantly affect RT. As can be seen in Figure 8 , the percent correct response was lower for digital information format than for the remaining levels of information format, regardless of the level of grouping principle, and regardless of the level of information density.

Insert Figure 8 about here

Under conditions of low and medium information density, the percent correct response for digital information was lower for sequential grouping than for functional grouping.

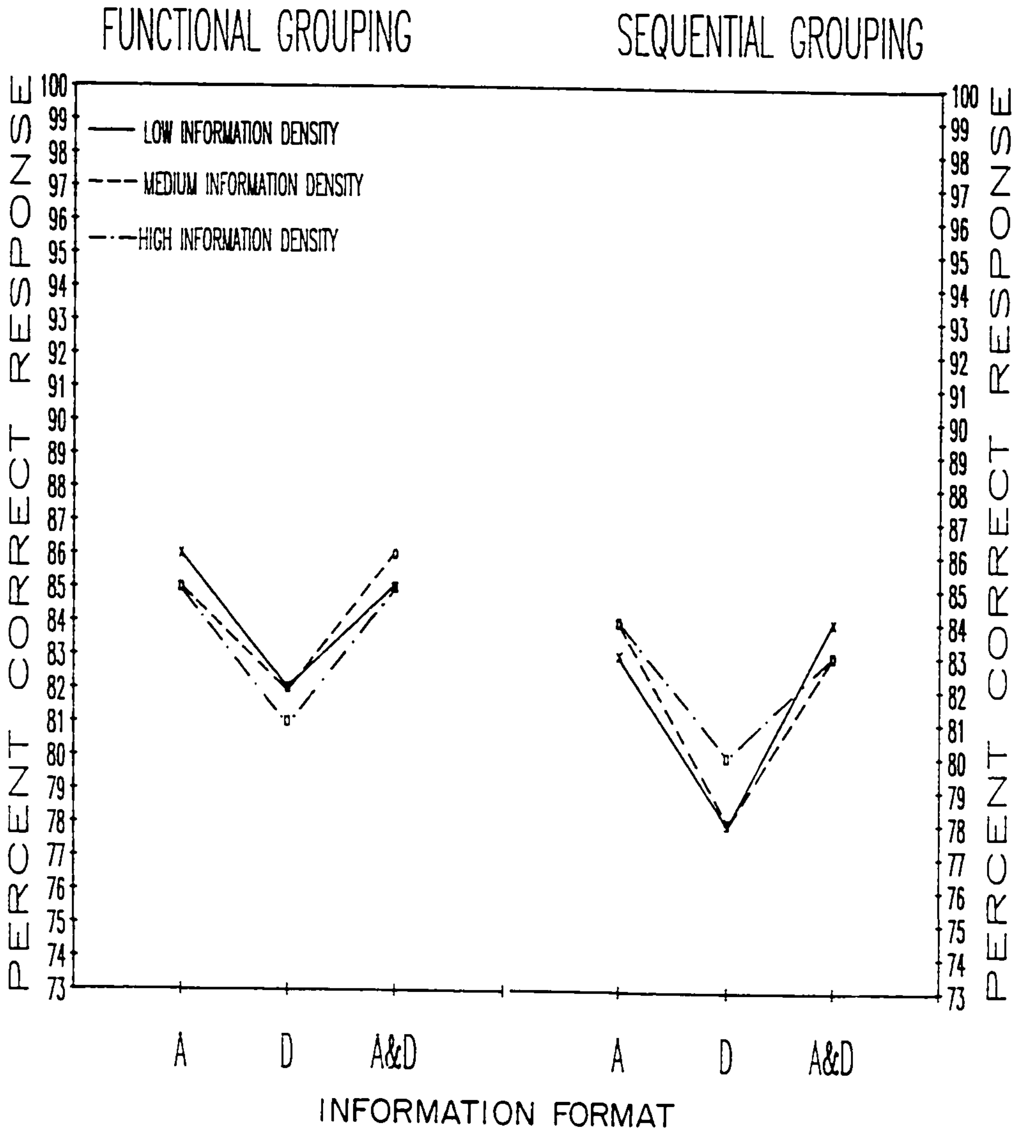

Figure 8. Percent Correct Response for Grouping Principle by Information Format by Information Density

However, for conditions of high information density, the percent correct response for digitral information format was not significantly different for sequential and functional grouping. Finally, for medium information density, the percent correct response for combined analogue and digital information format was significantly lower for sequential grouping than for functional grouping.

Discussion

The current study investigated the effects of task type, information format, information density, principle of information grouping, and orientation of the airspeed scale on RT and response accuracy in a decision making task.

Task Type Effects

It was hypothesized that task type would moderate the speed with which subjects responded to stimulus displays and the accuracy with which these responses were made. As predicted, responses for the current state estimation task were significantly faster, and significantly more accurate, than were responses to the future state estimation task. This effect held across single and dual task conditions.

The speed and accuracy advantages for the current state estimation task reflect the relatively low mental workload that characterized current state estimation. For current state estimation, the decision making task required only the identification of an instrument reading, and the comparison of this reading with a set of correct instrument readings. However, future system state could not be estimated from individual instrument readings. Future state estimation required subjects to consider the relationships between the readings on the three instruments, and to determine the implication of these relationships for future instrument readings. Thus, the mental workload level of the future state estimation task was greater than was the mental workload imposed by the current state estimation task.

Performance in the dual task condition affected estimates of current and future system state differently. For current state estimation, RT was significantly longer, and accuracy was significantly lower, in dual task conditions than in single task conditions. The transition from single to dual task performance exerted the opposite effect upon estimates of the future system state. For the future state estimation task, RT was significantly lower under dual task conditions than under single task conditions.

The divergent effects of transition from single to dual task conditions for estimates of current and future state appear to be the result of two main factors. First, the relatively short RT for dual task estimates of future system state probably reflects the effect of practice. This hypothesis is supported by the finding that, although estimates of future system state became more rapid under dual task conditions, the accuracy of future state estimates was not significantly different across single and dual task conditions. A practice effect for future, but not for current state estimation, would not be surprising, due to the relatively high mental workload, and the cognitive complexity, that characterized the future state estimation task.

A second phenomenon appears to explain the divergent effect of single versus dual task conditions on estimation of current system state. In dual task conditions, subjects appear to have sacrificed speed and accuracy for the estimates of current system state, while protecting RT and accuracy for estimates of future system state. This suggestion is supported by the fact that estimates of current system state were significantly less rapid and significantly less accurate in the dual task condition than in the single task condition.

Interaction of Task Type and Orientation of the Airspeed Scale

It was hypothesized that reversing the orientation of the airspeed scale would degrade performance more severely in conditions of future state estimation than in conditions of current state estimation. This hypothesis was based on the divergent cognitive demands of the current and the future state estimation tasks. In order to define correct readings for current state estimation, the subject was required only to determine if the instrument reading was within a specific range. If an instrument reading was not within the prescribed limits, it made no difference whether the reading was above or below the acceptable range. As a result, reversing the orientation of the airspeed scale was expected to have little effect on subjects' ability to determine whether instrument readings were correct or incorrect in current state estimation.

In order to estimate future system state, subjects were required not only to detect an incorrect instrument reading, but also were required to compare the direction of error across the three instruments in each stimulus display. In the future state estimation task, it was the relationship between the directions of error for the instrument readings that was the key to the correct or incorrect identity of each instrument reading.

Reversing the orientation of the airspeed scale created a display in which the relationship between error in the airspeed reading and error in the remaining instruments appeared to be reversed. For example, for displays with reversed orientation of the airspeed scale, an airspeed reading of 20 kt (e.g., below correct range) and an attitude reading of 06 degrees (e.g., above correct range) both were indicated by a scale pointer position that was on the top portion of the stimulus display. The spatial proximity of the two scale pointers was likely to convince subjects that a positive relationship existed between the direction of error for airspeed and the direction of error for attitude. Yet, in reality, a negative relationship existed. Thus, the reversal of the directional relationship between error in the instrument readings in reversed airspeed scale conditions was likely to confuse observers. As a result, it was hypothesized that reversing the orientation of the airspeed scale would increase RT severely, and also would decrease accuracy, for estimates of future system state.

The findings of the current study indicate that, as predicted, RT for the reversed airspeed scale condition was longer, and the percent correct response was lower, for future than for current state estimation. The RT difference between matching and reversed airspeed scales was approximately 1000 ms. for current state estimation, while the RT difference between matching and reversed airspeed scales was approximately 2200 ms for future state estimation. In addition, accuracy for future state estimation decreased from 84% for matching airspeed scales to 72% for not matching airspeed scales. These data support the hypothesis that reversing the orientation of the airspeed scale would degrade performance in the future state estimation task more severely than reversing the orientation of the airspeed scale would degrade performance in the current state estimation task.

Effects of Information Format in Single Task Conditions

For estimation of current system state, it was hypothesized that RT would be shortest for digital information format. For current state estimation, RT for digital information format was significantly shorter than was RT for analogue information format. Thus, it appears that, as hypothesized, subjects in current task conditions were able to determine the correct or incorrect identity of each instrument reading more rapidly by attending to the digital than the analogue information format. However, current task RT was not significantly different for digital and combined analogue and digital information formats. These findings indicate that subjects attended to the digital stimuli in both digital and combined analogue and digital information formats. Such a strategy would account for the failure of digital information format to obtain a speed advantage over combined analogue and digital displays under conditions of current state estimation.

RT was predicted to be shortest for the analogue information format under conditions of future state estimation. As predicted, analogue information format produced RT that was significantly shorter than the RT for combined analogue and digital displays, and that was significantly shorter than the RT for digital information format. However, the difference in RT between analogue and combined analogue and digital displays was much smaller than was the difference in RT between analogue and digital displays. The combined analogue and digital information format produced RT was approximately 500 ms longer than was the RT for analogue information format. However, digital information format produced RT that was almost twice as long as the RT for analogue information format. Thus, it appears that, as predicted, the digital information format strongly interfered with subjects' ability to comprehend the relationship between instrument readings in the future state estimation task. In addition, the relatively moderate difference in future task RT between analogue and combined analogue and digital information format may imply that subjects attended to the analogue scales in both analogue and combined analogue and digital displays.

Effects of Information Format in Dual Task Conditions

It was hypothesized that the combined analogue and digital displays would provide the most rapid performance overall in the dual task condition. This hypothesis was confirmed in the current study for dual task estimates of future system state. Under this task condition, RT for combined analogue and digital displays, and RT for purely analogue displays, was significantly shorter than was RT for the digital displays. The failure of digital and combined analogue and digital displays to produce RT that was significantly different indicates that under dual task conditions, subjects attended to the analogue scales when required to estimate future system state, whether they observed analogue or combined analogue and digital information format displays.

Combined analogue and digital displays also provided the shortest RT for dual task estimates of current system state. However, in this task condition, RT for the combined analogue and digital displays was significantly faster than was the RT either for purely analogue scales or for purely digital scales.

The fact that dual task RT for current state estimation was significantly faster for combined analogue and digital displays than for dual task RT for digital displays is somewhat curious. Combined analogue and digital displays were hypothesized to be superior in dual task conditions because they allowed subjects to select information from the format that best served each of the dual task demands. According to this hypothesis, subjects should have attended to the digital readings in order to make dual task estimates of current system state, whether they observed digital or combined analogue and digital displays. However, if this strategy had been adopted, the RT for digital information format should not have been significantly slower than was the RT for combined analogue and digital displays. An examination of the effect of the orientation of the airspeed scale on dual task RT for estimates of current system state helps to clarify this curious finding.

Interaction of Orientation of the Airspeed Scale and Information Format

RT for dual task estimates of current system state were not significantly different for combined analogue and digital information format than for digital information format in the matching airspeed scale condition. Thus, when the orientation of the airspeed scale matched the orientation of the remaining stimulus instruments, subjects appear to have attended to the digital readings in order to make dual task estimates of current system state. This strategy appears to have been adopted whether subjects were serving in the digital information format condition or were serving in the combined analogue and digital information format condition.

When the orientation of the airspeed scale was reversed, RT for dual task estimates of current system state was significantly longer for digital information format than for combined analogue and digital information format. In fact, under reversed airspeed scale conditions, RT for dual task estimates of current system state was over 1000 ms longer in the digital information format condition than in the combined analogue and digital information format condition. The fact that a significant difference in RT was found between digital and combined analogue and digital displays only in the reversed airspeed scale condition indicates that the combination of dual task demands, reversed airspeed scale, and digital information was troublesome when subjects attempted to estimate current system state.

Subjects who served under conditions of reversed airspeed scale were exposed to a different scale orientation for the airspeed instrument, depending upon whether the subjects were observing analogue or were observing digital displays. When serving in the analogue information format condition, subjects in the reversed airspeed scale group were trained to expect airspeed values above 120 kt to be represented by a scale pointer position that was low on the analogue scale, while airspeed values below 80 kt would be signified by a scale pointer position that was high on the analogue scale. However, when these same subjects observed digital displays, they were forced to think of an airspeed value above 120 kt as too high, and to consider an airspeed reading below 80 kt as too low.

Under single task conditions, the use of a different scale orientation for digital and for analogue displays did not appear to disrupt subjects' ability to judge current system state from digital displays. It was only when subjects were forced to determine both current and future system state from a single digital display (e.g., dual task conditions) that RT for current state estimation suffered.

This finding indicates that when subjects in the reversed airspeed scale condition were confronted with dual task demands, they used different strategies to estimate current system state and to estimate future system state from digital displays.

Estimation of current system state did not require subjects to determine the direction of error for incorrect stimulus readings. Rather, it was important only to determine whether or not the stimulus reading was within the range of correct values. This task probably could be accomplished most rapidly, and most accurately, by a direct comparison of the magnitude of the stimulus reading and the magnitude of correct instrument values. For example, an observer could determined quickly that a digital airspeed reading of 50 kt was below the lowest correct airspeed value (e.g., 80 kt). When comparing the magnitude of stimulus and correct instrument values, subject were, in fact, using a normal or matching orientation for the airspeed scale.

For estimates of future system state, it was necessary to consider the direction of error in an instrument reading, and to compare the direction of error across the three instruments within a stimulus display. The need to compare the directions of error probably stimulated subjects to compare a mental image of the stimulus readings with a mental image of correct instrument readings on an analogue display.

If subjects did compare mental images of stimulus readings with mental images of correct analogue readings in order to estimate future system state from digital displays, recent exposure to analogue displays with reversed airspeed scale orientation was likely to be troublesome. For example, experience with the reversed analogue scale would suggest to the subject that an airspeed reading of 50 kt was positioned <u>above</u> the range of correct airspeed values on the analogue scale. Yet, when estimating current system state from digital displays, the subject was trained to consider a value of 50 kt as below the range of correct airspeed values (e.g., 80 kt to 120 kt). Such a discrepancy may have encouraged subjects to rotate the reversed airspeed scale mentally in order to eradicate this discrepancy. Subjects also may have been prompted to recheck their perception of the direction of error across instrument readings in order to protect accuracy of response. Either action can account for the relatively long RT for dual task estimates of future system state in digital information format conditions. However, the decreased percent correct response that accompanied the increased RT in this stimulus condition indicates that subjects either were not always aware of their confusion, or were not always willing to expend the additional time and effort to enhance the accuracy of their responses.

In sum, under dual task and digital information format conditions, the use of divergent strategies to determine current and future system state was likely to be troublesome for subjects in the reversed airspeed scale group. This is because each strategy required the subject to consider a different scale orientation for the airspeed indicator.

Grouping Principle Effects

Grouping principle was hypothesized to affect RT only for task conditions in which subjects were required to consider the relationship between instrument readings. As hypothesized, a significant effect for grouping principle was obtained only for estimates of future system state. In single task conditions, RT for estimates of future system state were significantly shorter for sequential grouping than for functional grouping. However, the relatively rapid RT for sequentially grouped displays may have been the result of two main factors: 1) rapid transfer of information from the sequentially grouped displays to the observer; or 2) a speed-accuracy tradeoff. The significant interaction between grouping principle and task type for the percent correct response provides evidence that a speed-accuracy tradeoff was responsible for the relatively low RT obtained for sequential grouping.

For single task estimates of future system state, percent correct response was significantly lower for sequential grouping than for functional grouping. The combination of longer RT and higher percent correct response for functional grouping than for sequential grouping indicates that subjects in the functional grouping condition established a more stringent response criterion for estimates of future state than did subjects in the sequential grouping condition. The relatively low response criterion adopted for future state estimation by subjects in the sequential grouping condition may have been stimulated by the difficulty of determining the relationships between instrument readings on sequentially grouped stimulus displays. However, the precise cause of the variance in response criteria for future state estimation that was stimulated by the levels of grouping principle cannot be determined with certainty within the current methodological framework.

Effect of Information Density

The information density variable did not moderate overall RT in the current study. This finding is curious in light of the large body of evidence that confirms increases in RT as a function of increasing information density (Alluisi, 1970; Hurts & Halcomb, 1984; Smith, 1968; Stern, 1985; Sternberg, 1969).

The failure of the information density to moderate RT and accuracy in the current study probably was due to manner in which information density was operationalized. In order to create conditions of medium and high information density, extra symbols were added to each low information density display (see Appendices A and B). However, the symbols that were added to displays in order to create conditions of medium or high information density imparted no additional information to subjects. As a result, subjects probably learned to ignore the extra symbols relatively rapidly. In effect, the extra symbols soon were not perceived by subjects as members of the stimulus set. The failure of subjects to attend to the extra symbols that were used to create conditions of medium or high information density could explain the failure of the information density variable to obtain its traditional effect on RT in the current study.

According to subjects' informal comments, a second factor may have diluted the traditional effect of information density. For analogue and for combined analogue and digital displays, high information density was created, in part, by the addition of a vertical line along the side of the airspeed and the altitude scales (see Appendices A and B). Unfortunately, these extra lines were positioned in such a manner as to define the upper portion of the scale area that represented correct instrument readings. Several subjects reported that these extra vertical lines served as cues for the location of the correct reading area. Thus, in conditions of high information density, symbols that were intended to serve as clutter may have provided important information that was used by subjects to determine the correct or incorrect identity of an airspeed or altitude reading. If this was the case for the majority of subjects, the result would be dilution of the detrimental effect of high information density.

Conclusions

The results of the current study indicate that performance in a complex task often is moderated by the interactive effects of several independent factors. For example, the task condition in which subjects performed moderated the relationship between many independent and dependent variables. In some instances, task type determined whether or not a variable would moderate performance. In other situations, task type altered the strength of the relationship between an independent variable and the speed and accuracy of performance.

The type of task in which a subject performed moderated the effect of information format on subjects' performance. Information format was a vitally important factor in the future task condition where digital displays degraded performance severely, both in terms of RT and accuracy. However, digital displays did not slow RT or reduce accuracy for single task estimates of current system state. The implication of these findings is that display designers must consider the type of task that system operators will perform in order to determine the information format that will provide optimum performance.

Task type also moderated the effects of grouping principle. Specifically, the grouping principle variable moderated performance only in task conditions that required subjects to estimate future system state. Thus, the interaction between task type and grouping principle reflects the commonly accepted principle that the integration of information enhances performance only when there is a relationship between the information sources that are integrated. However, the current findings also indicate that, even when information is related, integrating the information will enhance performance only when the relationships between the pieces of information are of importance to the task at hand. For displays on which unrelated information is presented, reduction of the visual scanning demands of the display is likely to enhance performance more than will attempts to integrate information.

The interaction between task type and grouping principle provides a second recommendation for the design of complex displays. For task conditions that required subjects to estimate future system state, functional grouping obtained more accurate responses overall than did sequential grouping. However, this accuracy advantage was obtained at the expenses of increased RT. Thus, in order to determine which grouping principle will enhance performance most notably, a display designer must consider not only the task that the system operator will perform, but also must consider the performance objective. If it is most important for the operator of a complex system to estimate system state accurately, the functional grouping principle may provide the superior basis for the integration of information. However, if it is most important for system operators to respond rapidly to changes in system state, the functional grouping of information may be counterproductive to performance objectives. This possibility certainly deserves further research attention.

An accuracy advantage for functional displays was obtained only in the matching airspeed scale condition. This finding is not surprising in light of the fact that functional grouping is based on the practice of integrating task relevant data in order to underscore the relationships between these sources of information. Reversing the orientation of the airspeed scale provides a distorted image of such relationships. Thus, it is not surprising that accuracy was degraded for functional displays that employed a reversed airspeed scale orientation. The implication of this finding is that display designers must consider the overall objective of system operator performance when selecting each parameter of display design. It does little good to stress the relationship between several sources of information in one parameter of the display, if these same relationships are distorted by a second parameter of design.

In the current study, the orientation of the airspeed scale exerted a strong influence on the speed and accuracy of performance across experimental conditions. The suggestion to reverse the orientation of the airspeed scale resulted from pilot reports that the opposing movement of scale pointers on vertical airspeed and altitude scales often creates a false impression of horizontal roll (Miles et al., 1982). However, the proposed solution for this problem (e.g., reversing the orientation of the airspeed scale) seems to create more problems than it solves.

The practice of reversing the airspeed scale orientation may reduce the number of times a pilot perceives incorrectly that the aircraft is in a horizontal roll, but the practice is likely to increase the incidence of incorrect airspeed readings. The consequences of an incorrect perception of horizontal roll are much less likely to extract their cost in terms of equipment and human lives than are the consequences of determining that airspeed is too high, when, in fact, airspeed is too low. The negative effect of reversing the orientation of the airspeed scale was relatively strong in the current study. This finding not only provides evidence that reversing the orientation of the airspeed scale will degrade, rather than enhance pilot performance, but also underscores the importance of considering the effect of a change in display design on <u>overall</u> performance of the system operator.

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Appendix A

Experimental Displays

Appendix A

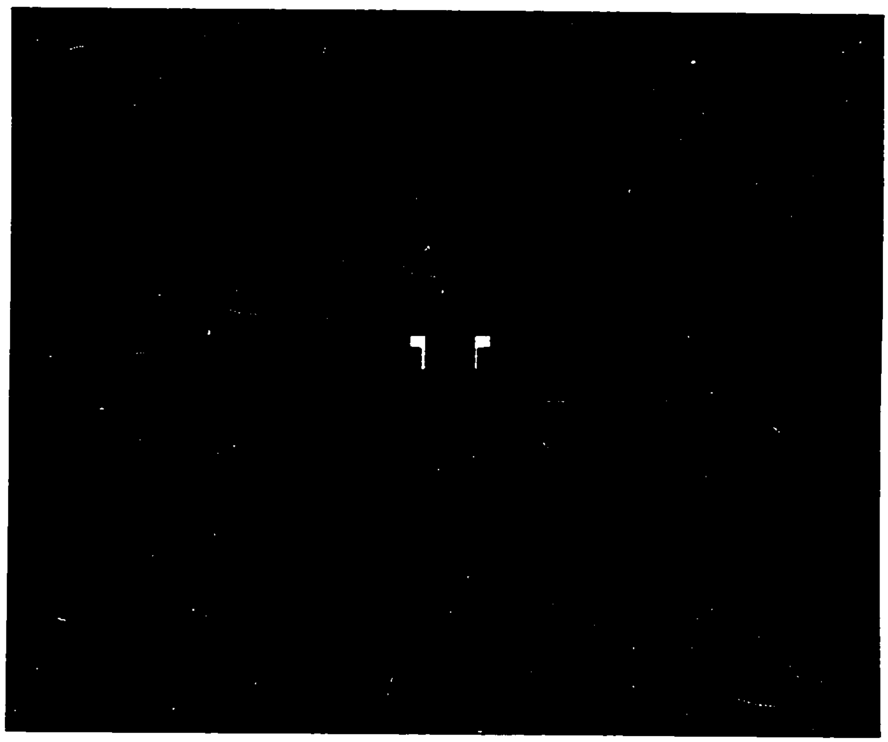

Figure 1. Display for Sequential Information Grouping, Analogue Information Format, and Low Information Density

(Appendix Continued)

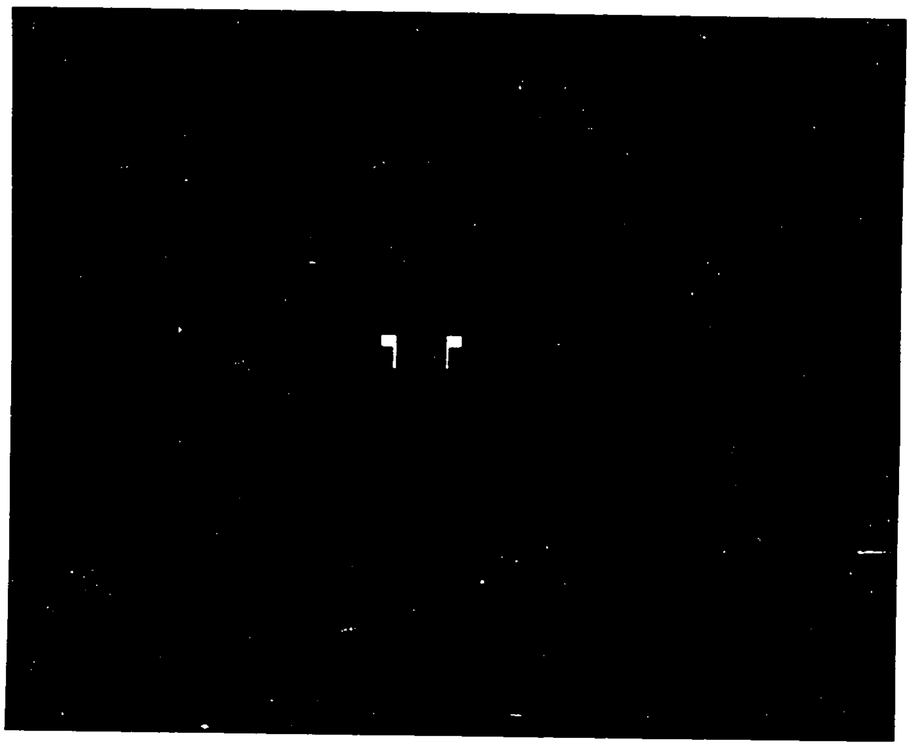

Figure 2. Display for Sequential Information Grouping, Analogue Information Format, and Medium Information Density

(Appendix Continued)

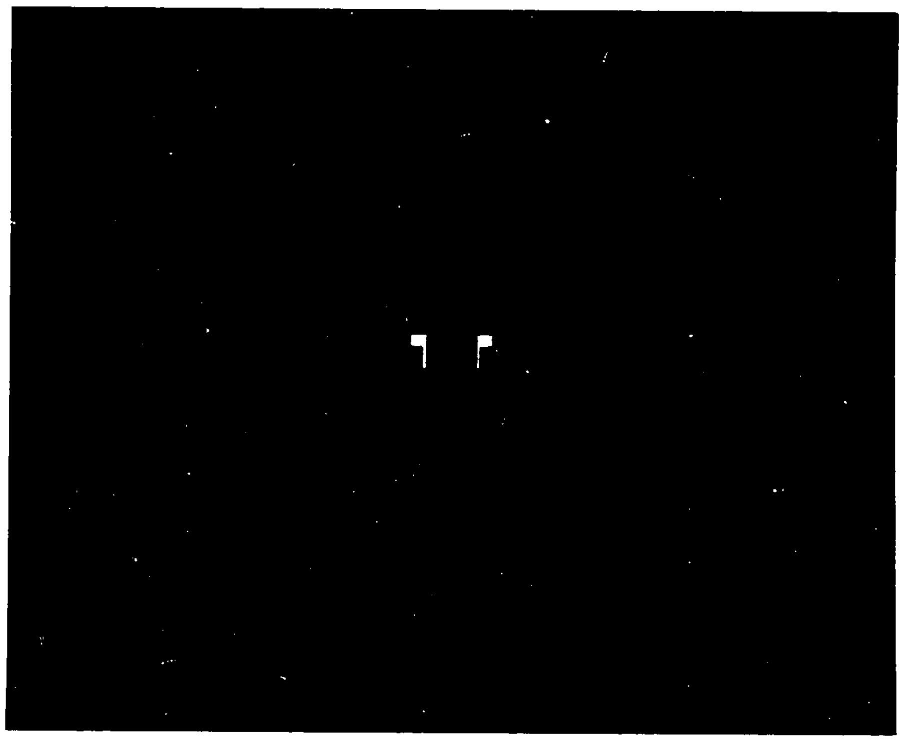

Figure 3. Display for Sequential Information Grouping, Analogue Information Format, and High Information Density

(Appendix Continued)

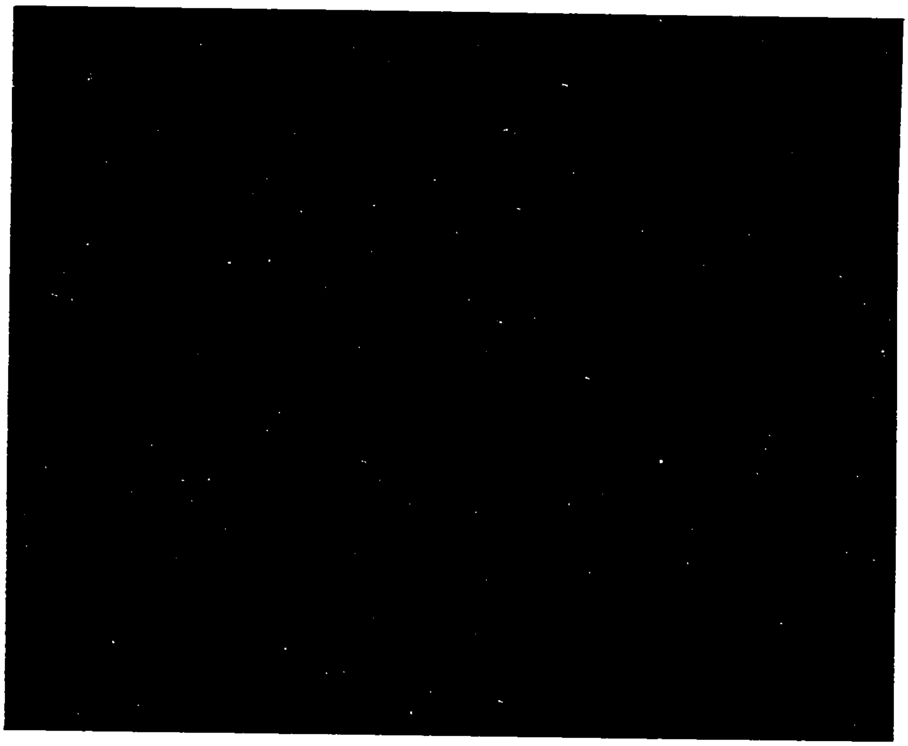

Figure 4. Display for Sequential Information Grouping, Digital Information Format, and Low Information Density

(Appendix Continued)

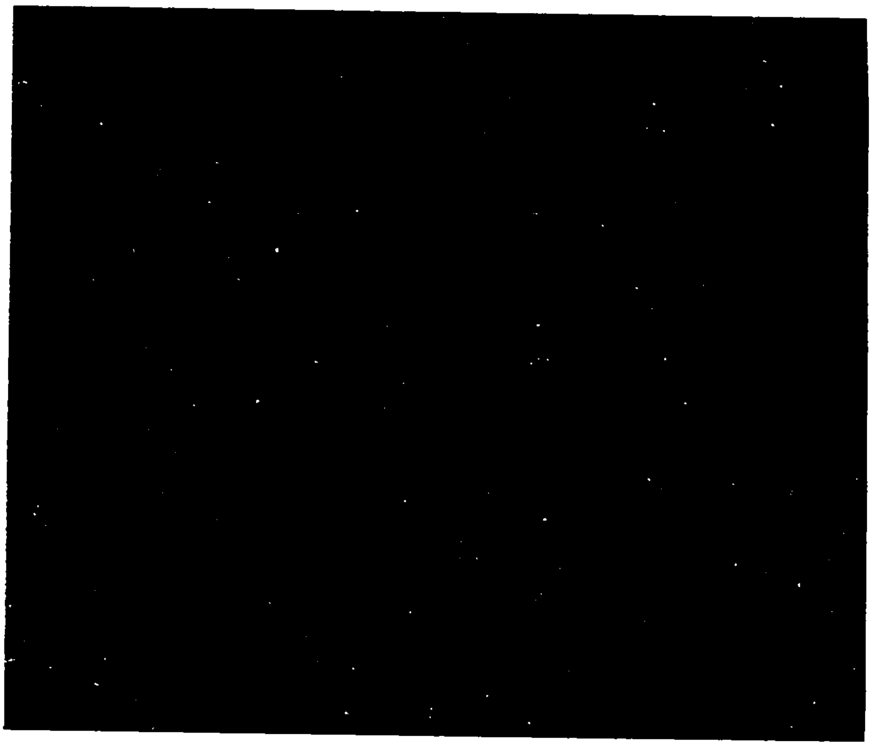

Figure 5. Display for Sequential Information Grouping, Digital Information Format, and Medium Information Density

(Appendix Continued)

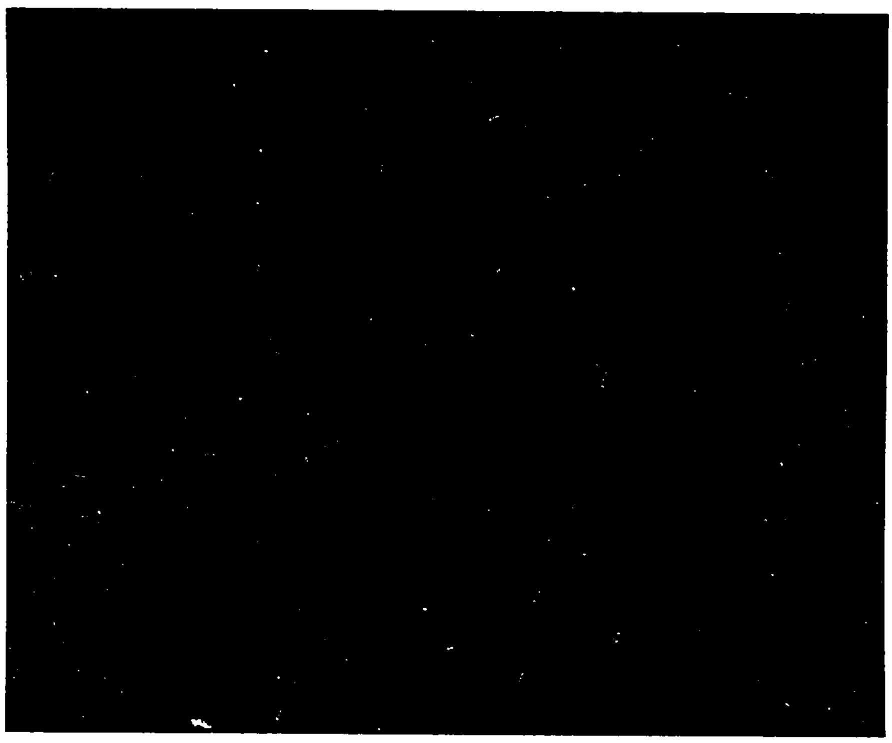

Figure 6. Display for Sequential Information Grouping, Digital Information Format, and High Information Density

(Appendix Continued)

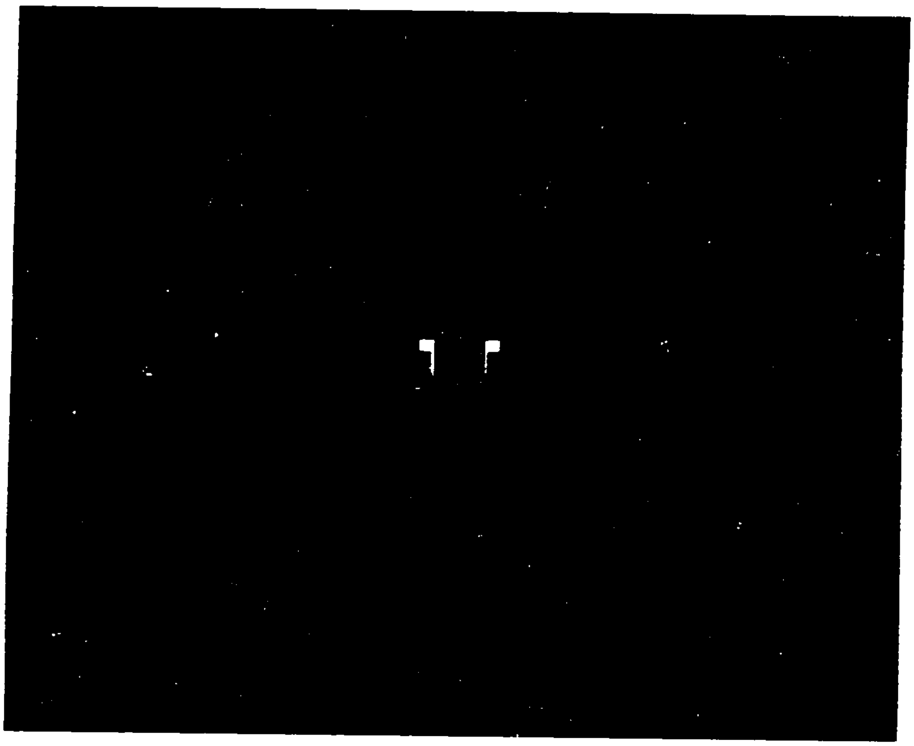

Figure 7. Display for Sequential Information Grouping, Combined Analogue and Digital Information Format, and Low Information Density

(Appendix Continued)

Figure 8. Display for Sequential Information Grouping, Combined Analogue and Digital Information Format, and Medium Information Density

(Appendix Continued)

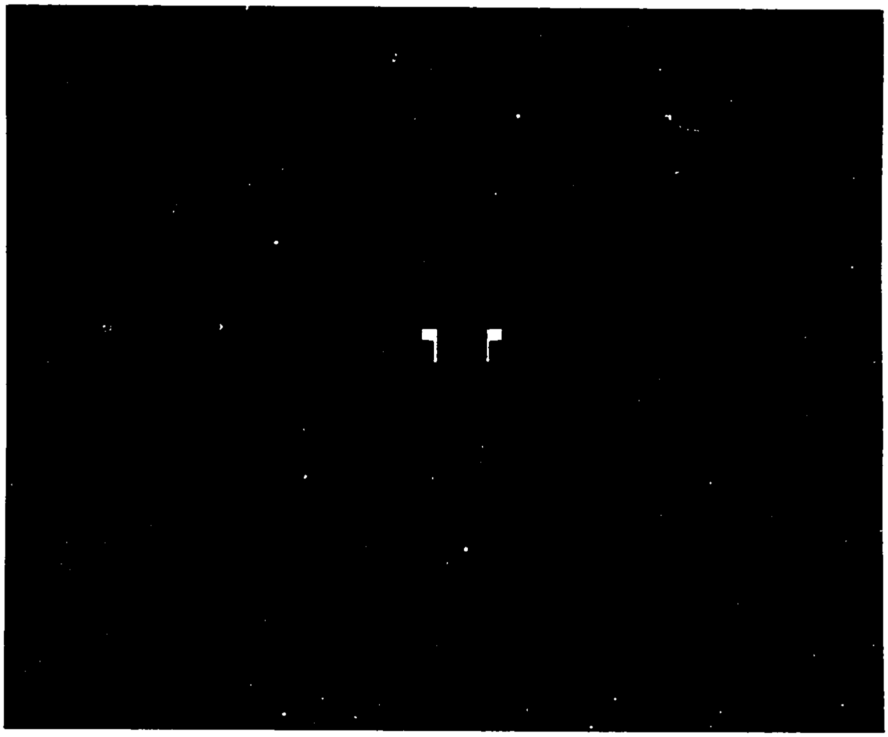

Figure 9. Display for Sequential Information Grouping, Combined Analogue and Digital Information Format, and High Information Density

(Appendix Continued)

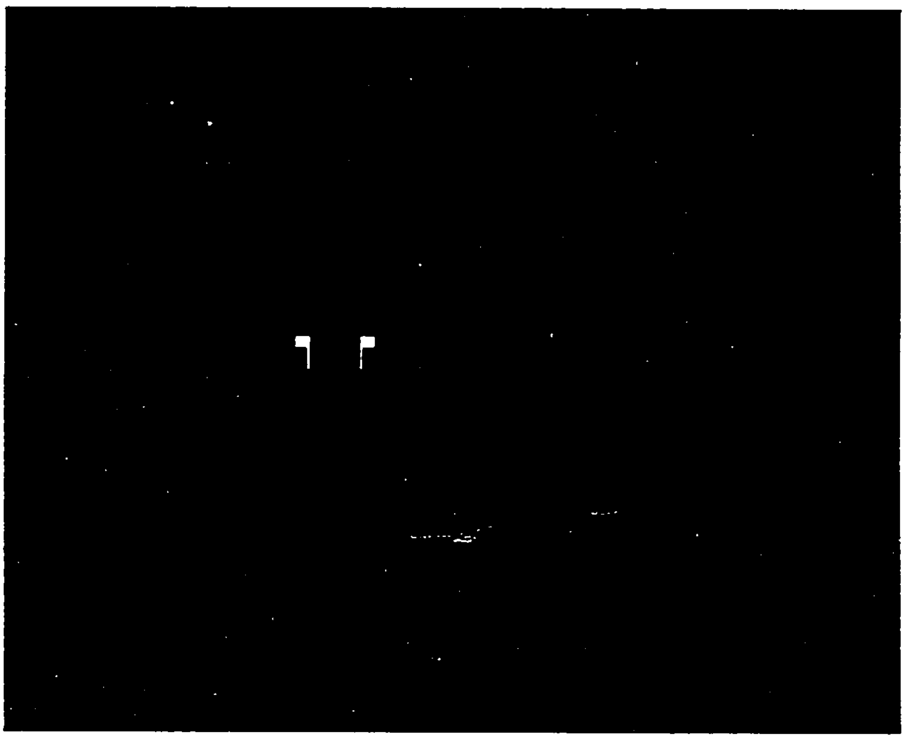

Figure 10. Display for Functional Information Grouping, Analogue Information Format, and Low Information Density

(Appendix Continued)

Figure 11. Display for Functional Information Grouping, Analogue Information Format, and Medium Information Density

(Appendix Continued)

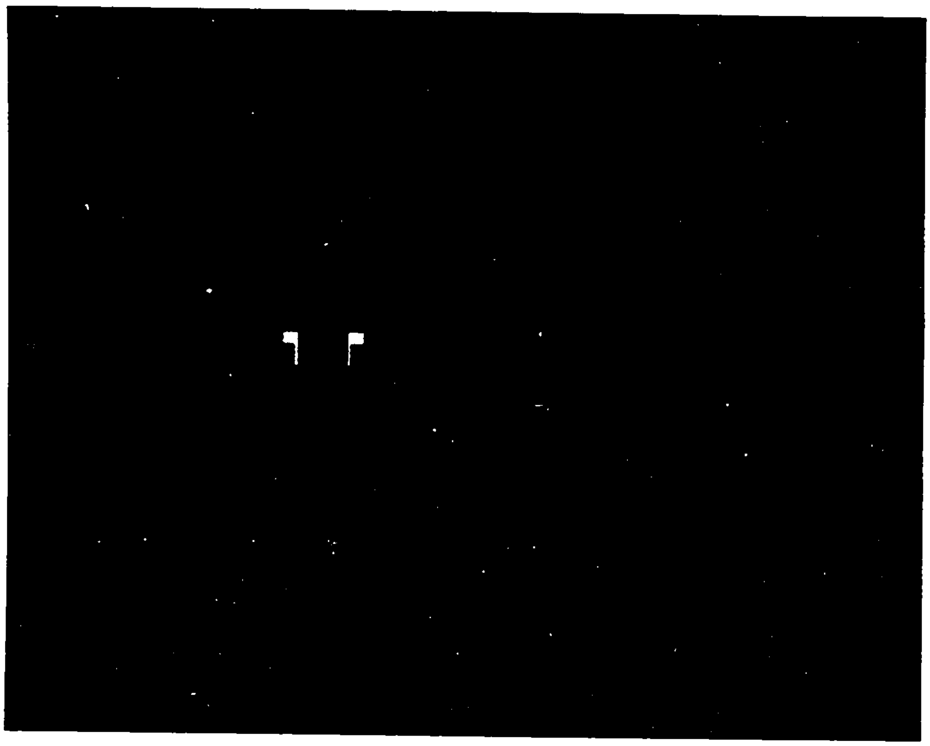

Figure 12. Display for Functional Information Grouping, Analogue Information Format, and High Information Density

(Appendix Continued)

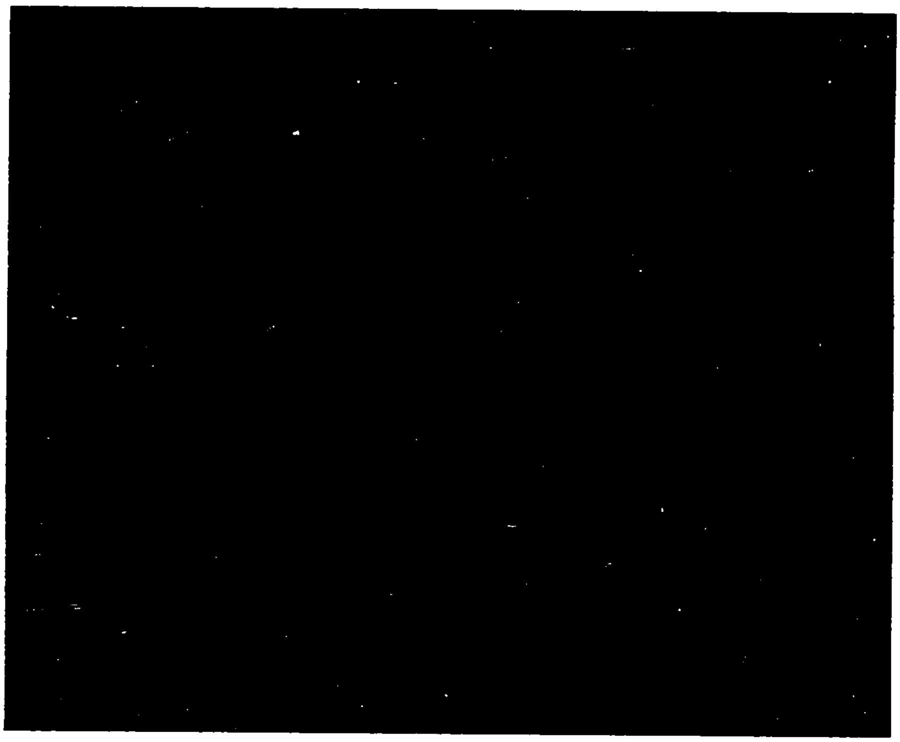

Figure 13. Display for Functional Information Grouping, Digital Information Format, and Low Information Density

(Appendix Continued)

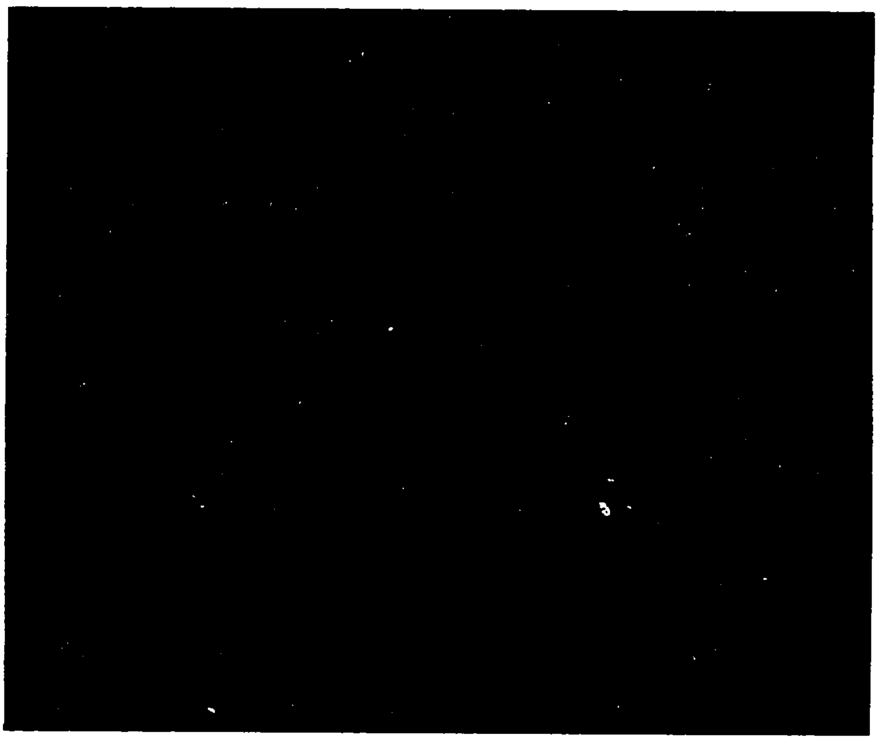

Figure 14. Display for Functional Information Grouping, Digital Information Format, and Medium Information Density

(Appendix Continued)

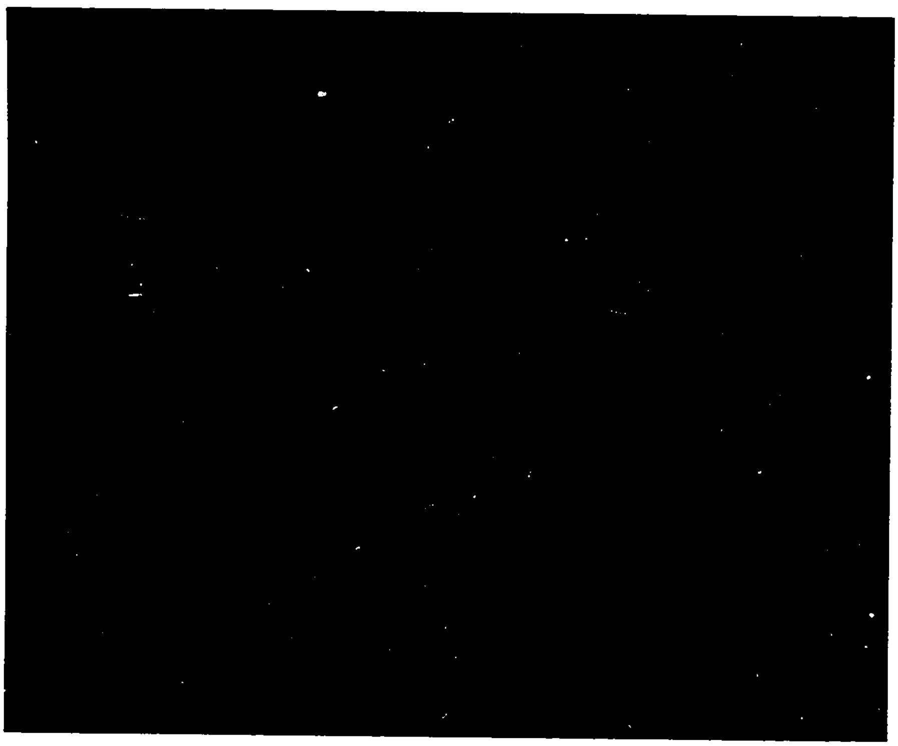

Figure 15. Display for Functional Information Grouping, Digital Information Format, and High Information Density

(Appendix Continued)

Figure 16. Display for Functional Information Grouping, Combined Analogue and Digital Information Format, and Low Information Density

(Appendix Continued)

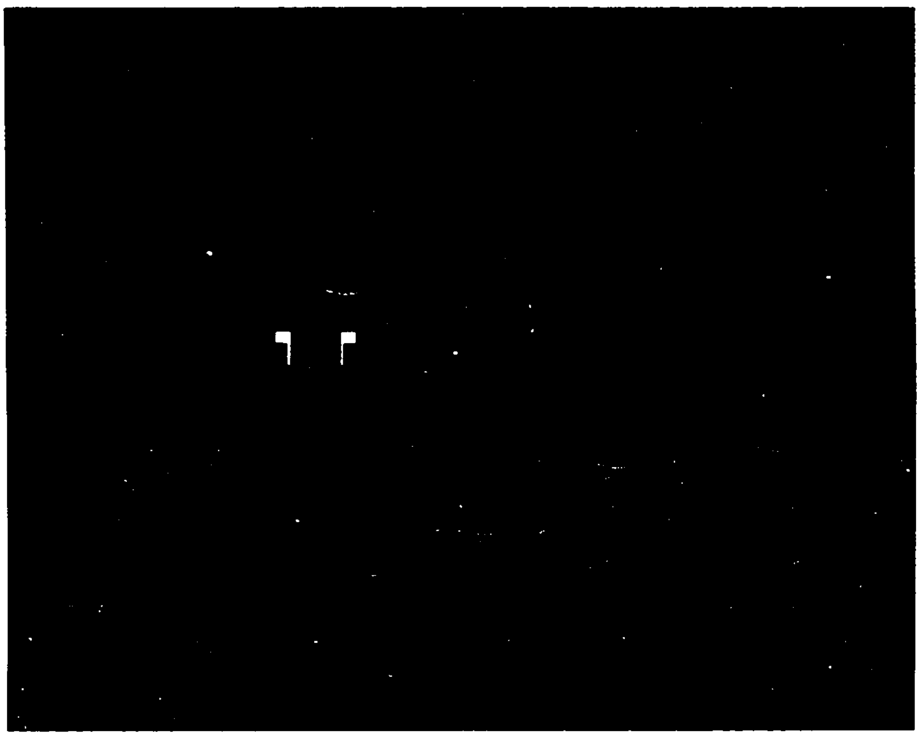

Figure 17. Display for Functional Information Grouping, Combined Analogue and Digital Information Format, and Medium Information Density

(Appendix Continued)

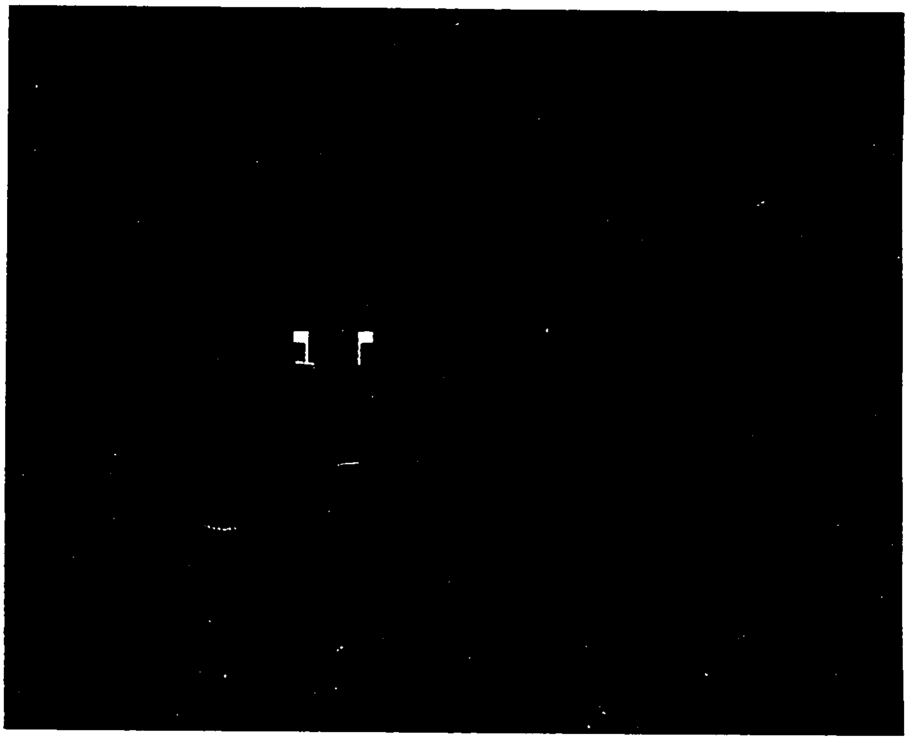

Figure 18. Display for Functional Information Grouping, Combined Analogue and Digital Information Format, and High Information Density

(Appendix Continued)

Appendix B

Description of Stimulus Display Configurations

Appendix B

Description of Stimulus Display Configurations

Grouping Principle

Sequential grouping was created by presenting the attitude reading in a central location on the display. The airspeed reading was placed on the left of the attitude indicator, while the altitude reading was positioned to the right of the attitude reading. Functional grouping was created by placing the attitude reading on the left side of the stimulus display. The altitude reading then was positioned to the near right of the attitude reading, while the airspeed reading was positioned to the far right of the altitude reading.

Information Format

Digital Information Format. Digital displays provided instrument readings in alphanumeric form. Each digital reading consisted of three numbers that were displayed in yellow against the dark green background of the CRT screen. The numeric symbols were .64 cm tall and .32 cm wide, and a space of .16 cm separated adjacent numbers. Thus, each three digit readout was 1.28 cm wide.

Digital altitude, attitude, and airspeed readings were presented in three equally spaced columns. The columns

(Appendix Continued)

were positioned so that the right edge of the first column was 6 cm from the left edge of the second column, while an equal distance separated the right and left edges of the second and third column, respectively. For both functional and sequential grouping conditions, the total width of a digital display configuration was 15.84 cm.

Analogue Information Format. In conditions of analogue information format, airspeed and altitude readings were presented on separate vertical scales that were characterized by fixed scales and moveing pointers. The vertical scales were drawn in white against a dark green background. The vertical scales were 15 cm tall, and major scale division marks were drawn at intervals of 2.54 cm. Minor scale division marks were positioned at equal intervals between the major scale division marks. Pointers on the airspeed and altitude indicators were small white triangles that were .64 cm long at the base and approximately .05 cm long at the tip. The position of the scale pointer varied across experimental trials.

The analogue attitude indicator consisted of nine vertically spaced "hash marks." The "hash marks" were drawn in white and were presented against a dual color background. The top half of this background area was blue, while the bottom half of the background area was brown. The "hash

(Appendix Continued)

marks" on the attitude indicator were .64 cm wide and a space of 1.27 cm separated each of the nine "hash marks." Thus, the total height of the analogue attitude indicator was 13.42 cm. The top edge of the airplane symbol served as the scale pointer for the attitude indicator. The two legs of the airplane symbol each were .64 cm tall and .32 cm wide. One leg of the airplane symbol was placed .48 cm away from each side of the "hash mark" space on the attitude indicator. Thus, the two legs were positioned 1.60 cm apart.

In sequential grouping conditions, the analogue indicator was separated from the right edge of the airspeed indicator, and from the left edge of the altimeter, by a space of 1.27 cm. Thus, in conditions of anlogue information format, the total width of the sequential grouping display was 18 cm. In functional grouping conditions, a distance of .64 cm separated the right edge of the attitude indicator from the left edge of the altitude indicator. However, a distance of 3 cm separated the right and the left edges of the altitude and airspeed indicators, respectively. Thus, the total width of the analogue display in functional grouping conditions was 19.70 cm.

Combined Analogue and Digital Information Format. The analogue instrument scales were presented in the

(Appendix Continued)

combined analogue and digital displays. However, a three digit reading that reflected the scale value signified by the analogue scale pointer was printed beside the analogue scale pointers. The digital readings were positioned .32 cm to the side of the airspeed and the altitude scale pointers. For the attitude indicator, a digital readout was placed in the center of the two legs of the airplane symbol. A space of .32 cm separated the left side of the digital reading from the right side of the airplane symbol. Similarly, a space of .32 cm separated the right side of the digital reading from the left side of the airplane symbol. All digital markings were printed in yellow, and digital readings were identical in size and shape to the digital markers described for the digital information format displays.

Information Density

Digital Information Format. For the digital information format condition, low information density was represented by the display of one digital readout for each of the three stimulus instruments. Due to the fact that each stimulus letter was .64 cm tall, the total height of the digital display under conditions of low information density was .64 cm.

(Appendix Continued)

Medium information density was created for digital displays by the addition of two digital distractor readings to the readout column of each instrument. One distractor reading was placed 3.18 cm above the stimulus reading while the second distractor reading was placed an equal distance below the stimulus reading. As a result, digital displays in the high information condition consisted of three rows of equally spaced alphanumeric readouts. The total height of a digital display in the medium information density condition was 8.28 cm.

High information density was created for digital displays by the addition of four distractor readings to the readout column of each of the three stimulus instruments. This procedure resulted in a total of two distractor readings above and two distractor readings below the stimulus readout. Thus, in the high information condition, digital displays consisted of five rows of equally spaced alphanumeric readouts. The rows of alphanumeric readouts again were separated by a space of 3.18 cm in the high information density condition. The total height of a digital display in the high information density condition was 15.92 cm.

Analogue Information Format. Low information density for the analogue and for the combined analogue and digital

(Appendix Continued)

configurations was represented by the presentation of the attitude, altitude, and airspeed indicators as described above with the addition of no graphic or alphanumeric distractor symbols.

Medium information density displays for analogue conditions were created by adding two graphic distractor symbols to the presentation area of each of the three instruments. The airspeed indicator and the altitude indicator both were supplemented with a small diamond shaped symbol and a small "++" symbol. Each of these symbols was .64 cm tall and .32 cm wide. For the airspeed indicator, the diamond shaped symbol was displayed .64 cm to the left of the uppermost scale division mark, while the "++" symbol was displayed .64 cm to the left of the lowest scale division mark. For the altitude indicator, the diamond shaped symbol was displayed .64 cm to the right of the uppermost scale division mark, while the "++" symbol was displayed .64 cm to the right of the lowest scale division mark. Distractor symbol placement for the airspeed indicator and for the altitude indicator was identical for sequential and for functional grouping displays.

For conditions of medium information density, the attitude indicator was supplemented with a "#" symbol and a "**" symbol. Again, both distractor symbols were .32 cm

(Appendix Continued)

tail and .64 cm wide. The "#" symbol was placed in the center of the lower edge of the altitude indicator, while the "**" symbol was displayed centrally on the upper edge of the attitude indicator.

Analogue displays representing high information density displayed the graphic distractor symbols employed in the medium information density condition. However, in order to create high information density conditions, two additional graphic symbols were added to the presentation area of each of the three instruments. Thus, each analogue instrument in the high information density condition was supplemented with a total of four graphic symbols.

In conditions of high information density, the airspeed and the altitude indicators were supplemented with three small Y-shaped markings and a vertical bar. The Y-shaped markings were positioned .64 cm from the inside edge of the airspeed and attitude scales. Each Y-shaped marking was .64 cm tall and .20 cm wide and a space of .10 cm separated adjacent symbol elements. The vertical bars each were 1.60 cm tall and .08 cm wide. One vertical bar was positioned .64 cm from the outside edge of the airspeed scale, while the second vertical bar was placed .64 cm from the outside edge of the altitude indicator. The lower edge of the

(Appendix Continued)

vertical bar was positioned at the midpoint of the vertical scales.

Two additional graphic symbols were added to the attitude indicator to create high information density. These symbols can be observed in Figure 12 of Appendix A. Both of the graphic symbols were .64 cm square. One distractor symbol was positioned at the lower right corner of the attitude indicator, while the second distractor symbol was positioned at the upper left hand corner of the attitude indicator.

Combined Analogue and Digital Information Format. For combined analogue and digital configurations, low information density was provided by presenting the attitude, altitude, and airspeed indicators with no added graphic or alphanumeric distractor symbols. Medium and high information density were created in the combined analogue and digital displays by a procedure that was similar to that described for the purely analogue display configurations. However, for the combined analogue and digital displays, the supplemental cues for each level of information density were divided evenly between alphanumeric and graphic symbols.

In order to create medium information density for combined analogue and digital displays, the "++" symbol was

(Appendix Continued)

displayed .64 cm to the left of the <u>lowest</u> scale division mark of the airspeed indicator, and .64 cm to the right of the <u>lowest</u> scale division mark of the altitude indicator. Both graphic distractor were identical to their counterparts in the analogue information format condition. A numeric distractor cue was presented .64 cm to the left of the top scale marker of the altitude indicator. A second alphanumeric cue was placed .64 cm to the right of the top scale division mark of the airspeed indicator. Both alphanumeric distractor cues were selected from the stimulus set created for digital information format.

High information density was created in the combined analogue and digital condition by the display of two graphic and two alphanumeric distractor symbols on each instrument presentation area. The vertical bars and the Y-shaped symbols were positioned as described above for analogue displays. In addition, two numberic distractor cues were drawn from the digital display stimulus set, and were added to the display area of the altitude indicator. One numeric distractor cue was positioned .64 cm to the right of the top scale marker, while the second distractor cue was positioned .64 cm to the right of the bottom scale marker. Two distractor cues from the digital display stimulus set also

(Appendix Continued)

were placed .64 cm to the left of the top scale division marker, and .64 cm from the left of the lowest scale division marker on the airspeed indicator.

Appendix C

Possible Instrument Readings for Each Stimulus Instrument

Appendix C

Possible Values for Aircraft Instrument Readings

Above Prespecified Range

Airspeed	Attitude	Altitude
190	+9	475
180	+8	450
170	+7	425
160	+6	400
150	+5	375
140	+4	350
130	+3	325

In Prespecified Range

Airspeed	Attitude	Altitude
110	+1	275
100	0	250
090	-1	225

Below Prespecified Range

Airspeed	Attitude	Altitude
070	-9	175
060	-8	150
050	-7	125
040	-6	100
030	-5	075
020	-4	050
010	-3	025

Appendix D

Possible Instrument Readings for

Current State Estimation Task Conditions

Appendix D

Possible Instrument Readings for Current State Estimation Task Conditions

Correct Instrument Readings

Airspeed	Attitude	Altitude
110	+01	275
110	+01	250
110	+01	225
110	+00	275
110	+00	250
110	+00	225
110	-01	275
110	-01	250
110	-01	225
100	+01	275
100	+01	250
100	+01	225
100	+00	275
100	+00	250
100	+00	225
100	-01	275
100	-01	250
100	-01	225
090	+01	275
090	+01	250
090	+01	225
090	+00	275
090	+00	250
090	+00	225
090	-01	275
090	-01	250
090	-01	225

(Appendix Continued)

Incorrect Readings on One Instrument

Incorrect Instrument Readings on Airspeed Instrument

Airspeed	Attitude	Altitude
150	000	250
040	001	225
160	-01	275

Incorrect Instrument Readings on Attitude Instrument

Airspeed	Attitude	Altitude
100	-07	250
090	005	275
110	-09	225

Incorrect Instrument Readings on Altitude Instrument

Airspeed	Attitude	Altitude
090	001	375
110	-01	075
100	000	425

(Appendix Continued)

Incorrect Instrument Readings on Two Instruments

Incorrect Readings on Airspeed and Attitude

Airspeed	Attitude	Altitude
170	-07	225
040	006	250
180	-08	225

Incorrect Readings on Airspeed and Altitude

Airspeed	Attitude	Altitude
060	000	150
070	001	425
170	-01	075

Incorrect Readings on Attitude and Altitude

Airspeed	Attitude	Altitude
110	009	475
100	-08	050
090	008	450

(Appendix Continued)

Incorrect Instrument Readings on Three Instruments

Airspeed	Attitude	Altitude
160	-06	100
070	003	325
140	-04	150
030	007	425
180	-08	050
060	004	350
130	-03	175
040	006	400
150	-05	125

Appendix E

Possible Instrument Readings for Future State Estimation Task Conditions

Appendix E

Possible Instrument Readings for Future State Estimation Task Conditions

Correct Instrument Readings With All Readings in Prespecified Range

Airspeed	Attitude	Altitude
110	001	250
110	000	275
110	000	225
110	-01	250
100	001	275
100	001	225
100	000	250
100	-01	275
090	001	225
090	000	275
090	000	250
090	-01	250
090	-01	225

Correct Instrument Readings with Low Airspeed, Low Attitude, and High Altitude Readings

Airspeed	Attitude	Altitude
070	-03	325
060	-04	350
050	-05	375
040	-06	400
030	07	425
020	-08	450
010	-09	475
060	-04	250
090	-01	275

(Appendix Continued)

Correct Instrument Readings with High Airspeed,

High Attitude, and Low Altitude Readings

Airspeed	Attitude	Altitude
130	003	175
140	004	150
150	005	125
160	006	100
170	007	075
180	008	050
190	009	050

(Appendix Continued)

Incorrect Instrument Readings with Incorrect Airspeed

Airspeed	Attitude	Altitude
070	-03	100
040	-06	025
090	-01	175
110	001	125
130	003	375
150	005	425
170	007	375

Incorrect Instrument Readings with Incorrect Altitude

Airspeed	Attitude	Altitude
020	-08	150
010	-09	075
060	-09	100
100	000	400
160	006	325
180	008	450
190	009	350

Incorrect Instrument Readings with

Incorrect Readings on ALL Instruments

Airspeed	Attitude	Altitude
190	-09	025
180	-08	050
170	-07	075
160	-06	100
150	-05	125
140	-04	150
130	-03	175
070	003	325
060	004	350
050	005	375
040	006	400
030	007	425
020	008	450

Appendix F

Possible Instrument Readings for Combined Current and Future State Estimation Task Conditions

Appendix F

Possible Instrument Readings for Combined Current and Future State Estimation Task Conditions

Correct Instrument Readings From Current Task Set

Airspeed	Attitude	Altitude
110	+01	275
110	+00	275
110	+00	225
110	-01	275
100	+01	225
100	+00	275
100	+00	225
100	-01	275
090	+01	275
090	+00	275
090	+00	250
090	-01	275
090	-01	250
090	-01	225

Correct Instrument Readings From Future Task Set With All Instrument Readings In Prespecified Range

Airspeed	Attitude	Altitude
110	-01	250
100	001	275
100	001	225
090	001	225

(Appendix Continued)

Correct Instrument Readings From Future Task Set

With Low Airspeed, Low Attitude, and High Altitude

Airspeed	Attitude	Altitude
070	-03	325
060	-04	350
040	-06	400
030	-07	425
010	-09	475

Correct Instrument Readings From Future Task Set

With High Airspeed, High Attitude, and Low Altitude

Airspeed	Attitude	Altitude
140	004	150
150	005	125
160	006	100
170	007	075
180	008	050

(Appendix Continued)

Incorrect Instrument Readings From Current Task Set

With One Incorrect Instrument Reading

Airspeed	Attitude	Altitude
150	000	250
100	-07	250
090	001	375
100	000	425

Incorrect Instrument Readings From Current Task Set

With Two Incorrect Instrument Readings

Airspeed	Attitude	Altitude
110	009	475
090	008	450
040	006	250
180	-08	225
070	001	425

Incorrect Instrument Readings From Current Task Set

With All Instrument Readings Incorrect

Airspeed	Attitude	Altitude
160	-06	100
070	003	325
180	-08	050
060	004	350
150	-05	125

(Appendix Continued)

Incorrect Instrument Readings From Future Task Set with Incorrect Altitude Reading

Airspeed	Attitude	Altitude
020	-08	150
060	-09	100
160	006	325
190	009	350

Incorrect Instrument Readings From Future Task Set With Incorrect Airspeed Readings

Airspeed	Attitude	Altitude
040	-06	025
090	-01	175
150	005	425
170	007	375

Incorrect Instrument Readings From Future Task Set With Incorrect Readings on ALL Instruments

Airspeed	Attitude	Altitude
170	-07	075
160	-06	100
140	-04	150
070	003	325
040	006	400

Appendix G

Transcript of Training Session for Subjects

Transcript of Training Session for Subjects

Introduction to Instruments

The study in which you are participating requires that you look at aircraft displays on a computer screen and respond to the displays by pressing keys on the computer keyboard. On each display, you will see three flight instruments: 1) an attitude indicator; 2) an altitude indicator; and 3) an airspeed indicator.

The attitude indicator reflects an aircraft's position in space. For example, an attitude reading of 000 degrees means that a plane is flying a level course and will not gain or lose altitude. When the attitude reading is above 000 degrees, the nose of the plane is pointed upwards and the plane is flying in an upward position, getting farther from the ground as it flies. A low or minus attitude reading means that the nose of the plane is pointed down, and the plane is getting closer to the ground as it flies.

The next instrument is the altitude indicator. The altitude indicator tells the pilot how many ft above the ground he or she is flying. So, an altitude reading of 300 ft means that the plane is flying 300 ft above the ground.

(Appendix Continued)

The last instrument is the airspeed indicator. The airspeed indicator simply tells the pilot how fast the plane is flying. In fact, the airspeed indicator is just like the speedometer in your car. So, an airspeed reading of 125 kt means the plane is flying at 125 kt.

Relationships between Instruments

The readings on the three instruments in each display are not independent of one another, but are related in various ways. First, let me explain the relationship between attitude and altitude. If the altitude reading is above 000 degrees, the plane will get farther away from the ground as it flies. This means that, when attitude is above 000 degrees, the altitude at which the plane is flying increases gradually. On the other hand, when attitude is below 000 degrees, altitude decreases gradually. In short, a positive attitude increases altitude while a negative attitude decreases altitude.

Pilots use the relationship between attitude and altitude to control their aircraft. When a pilot wants to decrease altitude, a control movement that reduces attitude below 000 degrees will result in a loss of altitude. On the other hand, if the pilot wants to increase altitude, a control movement that moves the attitude setting above 000 degrees will result in a gain in altitude.

(Appendix Continued)

Let me check to see if you understand the relationship between attitude and altitude. If the altitude is too high, what should the pilot do to correct the situation? If altitude is too low, what should the pilot do to correct the situation?

Now I'd like to explain the relationship between airspeed and altitude. When the nose of the aircraft is down, airspeed increases. This is easy to remember if you think of a bicycle going downhill. As a bicycle rider goes down a hill, he or she picks up speed, even without pedaling faster. The same thing happens to an airplane. On the other hand, when the nose of the aircraft is up, airspeed gets slower. So altitude and airspeed have a negative relationship. As altitude goes in one direction, airspeed moves in the opposite direction.

Let me check to see if you understand the relationship between altitude and airspeed. If altitude changes from 200 ft to 400 ft, what will happen to airspeed? If altitude changes from 400 ft to 200 ft, what will happen to airspeed now?

Reading the Instrument Scales

Let me explain how you will read the instruments that are in each flight display. The reading for the attitude

(Appendix Continued)

always is on the center of the display screen. The reading for the altitude indicator is on the left of the display, while the airspeed indicator is always on the far right. (Each instrument is shown to the subject on a cardboard training diagram that illustrates analogue scales of low information density).

As you can see, the instruments in the training diagram have no numbers on them. In some experimental trials, you will observe and judge instruments like this. So, sometimes you will have to determine instrument readings by looking at the position of the scale pointer.

In order to read the attitude scale, you will have to look at the position of the top edge of the airplane symbol. The area of the airplane symbol tells you what the attitude reading is. (The top edge of the airplane symbol is pointed out to the subject on the training diagram). In fact, you can consider the top edge of the airplane symbol to be a kind of scale pointer. But its important to know that, on the attitude indicator, the "hash marks," not the airplane symbol, move. So, the attitude indicator has a fixed pointer but a moving scale. The airplane symbol always is in the same central area on the attitude indicator. However, the background of the attitude scale moves so that the top of the airplane symbol may be in the brown or in the

(Appendix Continued)

blue area of the scale, and sometimes the top of the airplane symbol is positioned on the line where the blue and brown colors come together.

When the top edge of the airplane symbol is positioned at the middle "hash mark" on the attitude indicator, an altitude reading of 000 degrees is represented. The area above the middle "hash mark" signifies a reading above 000 degrees. This area is colored blue. That was done to help you remember that, when the airplane symbol is in the blue area, the nose of the plane in up and altitude will increase. When the top edge of the airplane symbol is positioned by a "hash mark" that is below the 000 degrees mark, the area behind the airplane symbol is colored brown. This should help you remember that, when the top of the airplane symbol is in the brown colored area, the nose of the plane is down, and the aircraft is losing altitude.

The values on the attitude indicator range from 10 to -10 degrees, with a difference of 002 degrees represented by the distance between each of the "hash marks." For example, a reading of 002 degrees is signified when the top of the airplane symbol is one "hash mark" above the boundary between the blue and brown background areas. If the top of the airplane symbol is positioned one "hash mark" up, a reading of 004 degrees is signified. Low attitude readings

(Appendix Continued)

are represented in the same way, but are found on the bottom half of the attitude indicator. For example, if the top of the airplane symbol is positioned one "hash mark" below the boundary between background colors, a reading of -02 degrees is demonstrated. An attitude of -04 degrees would be demonstrated when the airplane symbol is at the next "hash mark."

The altitude indicator is a vertical scale with a small diamond shaped pointer. On the altitude indicator, the scale remains constant while the small pointer is moved to signal the altitude reading. (The altitude indicator is illustrated to the subject on the training diagram). The values on the altitude indicator range from 000 ft to 500 ft. A reading of 500 ft is represented when the pointer is next to the top scale bar, while a reading of 000 ft is represented when the pointer is next to the lowest scale bar. When the scale pointer is at the middle scale bar, an altitude reading of 250 ft is signaled. On the altitude indicator, the distance between each scale bar represents a difference of 50 ft. For example, if the scale pointer is positioned at the lowest bar on the altitude scale, a reading of 000 ft is demonstrated. An altitude reading of 50 ft would be signified when the scale pointer is positioned at the next scale bar up.

(Appendix Continued)

The airspeed indicator is similar to the altitude indicator and you will read both instruments in the same way. However, values on the airspeed indicator range from 000 kt to 200 kt. A reading of 200 kt is represented when the scale pointer is at the top scale bar while a reading of 000 kt is represented when the pointer is at the lowest scale bar. So, the middle bar of this scale is equal to an airspeed reading of 100 kt. The distance between each scale bar on the airspeed scale represents a difference of 20 kt. For example, a reading of 200 kt is signified when the scale pointer is at the top bar on the airspeed indicator scale. If the scale pointer is positioned at the next highest bar on the airspeed scale, a reading of 180 kt is demonstrated.

Lets take a minute to make sure that you understand how to read each of the instruments. I am going to show you four sample displays and for each one, I would like you to tell me the reading that is signaled by each instrument. (Subject is shown a sample display containing the three stimulus instruments).

Correct and Incorrect Instrument Readings

The reading for each instrument in the display can be correct or incorrect. Lets look at correct and incorrect readings for each instrument. For the attitude indicator, the readings between 02 and -02 degrees are correct. The

(Appendix Continued)

correct range includes the values of 02 degrees and -02 degrees. So, attitude readings of -02, -01, 000, 001 and 002 are all correct. All other readings for attitude are incorrect. If you look at the training diagram, you can see the areas on the scale that represent correct and incorrect values for attitude.

For the altitude indicator, readings between 200 ft and 300 ft are the only correct readings. Again, 200 ft and 300 ft are considered correct readings. In addition, altitude readings of 225 ft, 250 ft, and 275 ft are correct. As before, all instrument readings that are not within the range of 225 ft and 275 ft are incorrect. You can see the scale areas that represent correct and incorrect altitude readings if you look at the altitude indicator on the training display.

Correct readings for the airspeed indicator lie between 80 kt and 120 kt. So, for airspeed, the correct readings are 80 kt, 90 kt, 100 kt, 110 kt, and 120 kt. All other airspeed readings are incorrect. The training display illustrates the areas of the airspeed scale that represent correct and incorrect values.

Do you have any questions about what values represent correct and incorrect readings for any of the three instruments? Let me check to make sure you know how to

(Appendix Continued)

determine correct and incorrect readings for each instrument. I am going to show you two more training displays. Please tell me what reading is signified by each instrument on the displays, and whether or not the reading for each instrument is correct or is incorrect.

<u>Instructions for Current State Estimation Task</u>

Now I'd like to tell you what your task will be in the experiment. When a flight display of three instruments appears on the screen, you are to determine the reading for each instrument, decide whether this reading is correct or incorrect, and signal your decision about each instrument reading by pressing a key on the computer keyboard. Remember, you are to signal either a correct or an incorrect response for <u>each</u> of the three instruments that you will see on each display.

<u>Instructions for Future State Estimation Task</u>

In this task, I am going to ask you to examine the readings on the three instruments on a display and determine if the three instrument readings <u>in combination</u> represent a condition that would preserve or return the aircraft to prespecified flight limits. In order to complete this task, you will have to remember the relationships between instrument readings that we talked about earlier. Remember that a positive attitude increases altitude but decreases

(Appendix Continued)

airspeed. For purposes of this task, you can assume that, if the attitude indicator is positioned one "hash marker" above the 000 degree mark, altitude will go up a distance of one scale marker, while airspeed will go down to a degree equal to one scale marker. In order to complete this task, consider that the attitude reading represents a control movement that you have just made. Next, determine how this change in attitude will impact airspeed and altitude.

In this task, a specific indicator reading may be incorrect at the current moment but still be in correct position to bring a second parameter back to prespecified flight conditions. For example, you may see that attitude is at -06 degrees, and that altitude is at 400 ft. In this case, the attitude and altitude readings are correct because the low attitude setting will return the high altitude to the correct reading zone. You can see this by noticing that the airplane symbol on the attitude indicator is three scale markers below the 000 degree mark, while the pointer on the altitude indicator is three scale markers above the center of the correct altitude range. Thus, the negative position of the attitude indicator will compensate for the high altitude readings.

In some displays, two instruments may be correct, but the third instrument may be incorrect. For example, if

(Appendix Continued)

attitude is -06 degrees, altitude is 400 ft, and airspeed is 160 kt, the attitude and altitude values would be correct, while the airspeed value would be incorrect. This is because the negative attitude setting will decrease the high altitude and bring it back to the correct range. However, the negative attitude setting also will increase the airspeed reading, and airspeed is already too high.

Lets take a minute to make sure that you understand how to determine correct and incorrect readings for each of the instruments in this task. I am going to show you six sample displays and, for each display, I would like you to tell me whether or not the readings for each instrument are correct or incorrect. Remember, you must give a response for each instrument. Don't feel that you have to hurry your responses at this point. I am most interested in making sure that you know how to judge correct and incorrect instrument readings.

(The subject is shown three correct training displays, one incorrect airspeed training display, one incorrect altitude display, and one display in which no instrument is correct. If the subject makes an incorrect response for any of the training displays, the error will be discussed and the subject will respond to one additional correct and one

(Appendix Continued)

additional incorrect sample display that represents the error type for which the subjects made an incorrect response).

<u>Signaling a Response</u>

Let's talk about how you will signal your responses. Please rest the pointer, index, and third finger of your right hand on the "H," "J," and "K" keys of the computer keyboard. This hand position is the "resting position." You must have your fingers positioned this way before you begin the experiment. In addition, return your fingers to this position after you have responded to all of the instruments in each stimulus display.

The response key for a correct attitude reading is the "Y" key while the response key for an incorrect attitude reading is the "N" key. The response key for a correct altitude reading is the "U" key while the key that signals a response of incorrect altitude is the "M" key. Finally, in order to signal a response of correct airspeed reading, the "I" key should be pressed. A response of incorrect airspeed reading should be signaled by pressing the "," key. (Correct and incorrect responses for each instrument are demonstrated on the computer keyboard.)

(Appendix Continued)

Notice that the left response key signals a judgment about the left instrument on the screen, while the middle response key signals a judgment about the middle instrument on the display screen. Of course, the right response key corresponds to the instrument on the right of the display. Also, notice that to make a response of "correct" for any instrument, you always move your finger to the key above the resting position key for that instrument. On the other hand, you always move your finger to the key below the resting finger key in order to make a response of "incorrect."

Let me make sure you understand how to make a correct and an incorrect response for each instrument. Why don't you show me how you would make a correct response for airspeed? Now show me an incorrect response for attitude. Finally, show me how you would make an incorrect response for altitude.

<u>Study Procedure</u>

You will see 28 different displays in a row. Each of these displays will be similar to the ones I've shown you in the training session. Once you have made a response for each of the three instruments, the display will disappear from the computer screen. In a couple of seconds, a new display will appear. Respond to the instruments in this

(Appendix Continued)

display, and the instruments in all subsequent displays, in the same way as you responded to the instruments in the first display. When you have completed the first 28 displays, a message that says, "You have completed 28 trials," will appear on the upper left hand corner of the computer screen. When you see this sign, please don't touch any keys on the computer keyboard, or you will disturb the recording of your responses. When the sign appears on the computer screen, just relax. I will tell you about the next displays that you will see, and then I will let you start the next set of trials. After each three sets of trials, you will be given a short break.

Accuracy Instructions

When you respond to the instrument readings, it is important to be very accurate. You must make your responses 95% accurate. This means that, of the 84 instruments that you will see in a set of 28 displays, a mistake can be made in responding to only four instruments. As long as you are sure that your responses are 95% accurate, respond to the displays as quickly as you can. But do not respond so quickly that your accuracy falls below the 95% mark.

Before we begin the experiment, do you have any questions about anything we have discussed in the training session?